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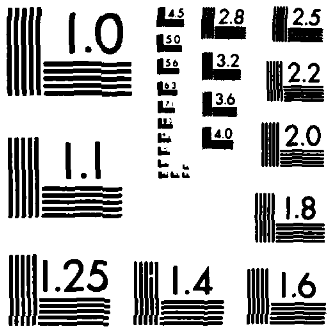

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PROCEEDINGS OF A WORKSHOP ON RADIOFREQUENCY RADIATION BIOEFFECTS

11-13 September 1984

DEFENSE RESEARCH GROUP, PANEL VIII
NATO AC/243

Editor: John C. Mitchell, B.S. (USAFSAM/RZP)

April 1985

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USAF SCHOOL OF AEROSPACE MEDICINE
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NOTICES

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This report has been reviewed and is approved for publication.

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The workshop was convened to address new developments in the setting and application of RFR safety standards, assessment of RFR levels in the military environment, RFR instrumentation and dosimetry, the medical approach to specific problems, and important state-of-the-art research regarding the biological effects of long-term low-level RFR exposures, pulsed versus continuous wave effects, and the effects of unique pulse modulations. The collected papers represent the contributions of various experts in the field from the NATO countries, brought together under the sponsorship of Defense Research Group, Panel VIII, NATO AC/243, at the Research Establishment for Applied Science, D-5307 Wachtberg-Werthhoven, Federal Republic of Germany.

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PREFACE

Research Study Group 2 (RSG2) of NATO AC/243 Defense Research Group Panel VIII conducted a radiofrequency radiation workshop in the UK 6-8 April 1981 to conclude its official activities. The proceedings were published as an Aeromedical Review (USAFSAM Review 3-81) in September 1981. In closing out the activities of RSG2 in 1981, the Panel VIII members indicated they would like to consider another such workshop in 1984.

In August 1983, Mr. H. Bakland informed me that Panel VIII would be pleased to receive a proposal to conduct another workshop in 1984. My proposal was forwarded to Panel VIII in October 1983 and was approved in November 1983.

The Radiofrequency Radiation (RFR) Bioeffects Workshop was conducted 11-13 September 1984 as planned. The workshop was held at the Research Establishment for Applied Science, Wachtberg-Werthhoven, Federal Republic of Germany. About 40 persons from five countries attended. The presentations were of high quality and elicited good audience participation. Based on the comments received from participants and attendees, this workshop provided a significant and effective update on the state-of-knowledge regarding the biological effects of RFR and current developments in the setting of new RFR safety standards.

The topics presented covered (1) the fundamentals of how RFR fields interact with biological systems, (2) the physiological response of RFR-induced thermal burdens, (3) the past and present knowledge of the biological effects of RFR, (4) data gaps and future research projections, (5) the development and application of new RFR safety standards (including a number of European standards), (6) the biological effects of long-term low-level (nonthermal) RFR, (7) the results of human exposures to RFR, (8) the operational concerns of some specialized RFR emitters, and (9) the assessment of occupational and environmental RFR exposures.

The major conclusions reached are summarized as follows:

(1) Significant advances have been made during the past 3-4 years in our understanding of the way RFR fields interact with biological systems and of the RFR-induced thermoregulatory response of animals and humans.

(2) RFR safety guidelines developed and adopted over the past few years have a better scientific basis (frequency dependent) and offer added protection. Some examples are ANSI (Sep 1982); ACGIH (May 1983); IRPA (Jul 1983); FRG (Jul 1984).

(3) Although whole-body specific absorption rate (SAR) has become widely accepted as the basis for the new RFR safety guidelines, there is a pressing need to develop a better understanding of localized SAR in humans to assess potential bioeffects resulting from highly concentrated absorption patterns.

(4) The RFR safety guidelines developed in the past 2 years used an average whole-body SAR of 4 W/kg in small laboratory animals as the adverse effects threshold. Some recent research findings suggest the actual threshold in animals may be closer to 1 W/kg, but this is not confirmed.

(5) New RFR research must be focused on mechanisms to resolve current controversies over the biological significance of RFR-induced phenomena such as calcium movement in biosystems, frequency and intensity effects, magnetic field effects, and resonance effects. These so-called nonthermal effects cannot be dismissed at this time.

(6) Current safety guidelines seem reasonably well supported in the frequency range of 30-1000 MHz, but additional work is needed to establish an appropriate peak power limit and to refine safety guidelines in the frequency bands 10 KHz-3 MHz and 20-300 GHz. Also it may be appropriate to develop a safety guideline for magnetic fields.

(7) Although STANAG 2345 allows personnel exposures considerably higher than most of the new RFR standards, the consensus of the workshop participants was that we should not recommend a revision at this time. A reasonable consensus is emerging on peacetime RFR standards.

(8) It is important that today's RFR bioeffects research results, emerging from many countries, continue to be disseminated as efficiently as possible for consideration and use by the NATO military organizations.

John C Mitchell
JOHN C. MITCHELL, Chairman
Radiofrequency Radiation Workshop

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WELCOME ADDRESS TO ORGANIZERS AND PARTICIPANTS OF THE WORKSHOP ON RADIOFREQUENCY RADIATION BIOEFFECTS

Prof Dr. R. Bernotat
Chairman Panel VIII Defense Research Group, NATO
Director of the Research Institute for Human Engineering

Mr. Mitchell, Ladies and Gentlemen,

I wish to extend a warm welcome to you here in Werthhoven. My words of welcome and my interest in this workshop have two sources:

--As the director of the institutes here in Werthhoven, I am responsible not only for the institute's work but also for the health of its personnel. Being subjected to radar radiation from time to time, we would like to know what the short-term or long-term effects of radiation to the human being can be.

--As the present chairman of Panel VIII, "Defense Application of Human and Biomedical Sciences," which sponsors this workshop, I have to say that this panel has been and is responsible for fostering and coordinating research in your area as well as for transferring knowledge to applications.

I wish to say a few words concerning the origins of this meeting, traces of which go back to 1970 when France proposed to Panel VIII, "Physics and Electronics," to set up a group on protection against nonionizing electromagnetic radiation. When Panel VIII was founded exactly 10 years ago in September 1974, it took over the well-prepared Terms of Reference for such a group and started the Research Study Group 2 on this same topic. After years of work this group organized, under the leadership of Mr. Mitchell, an excellent workshop in April 1981 in Farnborough in the UK. Results presented clearly showed that the thermal effects of electromagnetic radiation on the human body were relatively well understood. Much remained to be done, however, especially in the area of nonthermal effects; and it became clear that research activities in this area were limited to very few nations and very few researchers.

Research Study Group 2 was disbanded for a time, with the understanding that Panel VIII would be willing to take the topic up again if necessary. We asked Mr. Mitchell to keep in contact with the group members and to come back in 3 or 4 years with another workshop directed to the nonthermal effects. And here we are.

We hope to find out from today's meeting what the state of the knowledge is in this area and where important research gaps have to be filled. The knowledge of nonthermal effects of radiation can further help to protect military and civilian personnel against unwanted radiation effects. The panel has the possibility to spread this information via the appropriate NATO channels and to stimulate research in specific areas. A list of conclusions from this workshop in this sense would be helpful.

I. INVITED PAPERS

PHYSICAL INTERACTIONS OF RADIOFREQUENCY RADIATION FIELDS AND BIOLOGICAL SYSTEMS

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INTRODUCTION

In recent years, there has been growing interest in possible health hazards caused by the ever-increasing use of radiofrequency (RF) electromagnetic equipment and the resulting increased exposure of both occupational workers and the general public to RF radiation (RFR). (RF is defined as the frequency range from 10 kHz to 300 GHz.) An essential part of research related to biological effects produced by exposure to RF fields is the study of how electromagnetic fields interact physically with biological systems. Dosimetry, the calculation and measurement of the internal RF fields produced in an object exposed to RFR, is a principal component in the study of the physical interaction of RFR and biological systems.

Dosimetry is very important because biological effects are related to the internal fields in the body, which are not the same as the incident fields of the radiation. Determination of the internal fields, either by calculation or measurement, is often very difficult. Generally speaking, the internal fields are a function of the incident fields, their frequency, the size and shape of the object, and its electrical properties. Thus for a given incident radiation field, the internal fields in an object of a given size and shape may be quite different from the internal fields in a different object.

The purpose of this paper is to describe in general terms the common theoretical and experimental methods used in dosimetry, along with some results and a summary of what can presently be done. The paper is written primarily for those who are not electrical engineers or physicists. A minimum of mathematical details is included. There is no exhaustive description of what is to be found in the literature on dosimetry, and no attempt has been made to be all inclusive. Only RFR dosimetry as applied to models of people and animals is treated. This paper is similar to one contained in the proceedings of the previous radiofrequency radiation workshop conducted by Research Study Group 2 of NATO AC/243 Defence Research Group Panel VIII (published as USAFSAM Aeromedical Review 3-81, September 1981, by the U.S. Air Force). For convenience of the reader, a major part of the background material and description of previous work in dosimetry from that paper are included here.

In determining the internal RF fields inside an irradiated object, there is a need for both theory and experiment. The theory is needed to provide 1) explanations of how the internal fields depend on the characteristics of the incident fields and the absorber, 2) an understanding of cause-and-effect relationships, and 3) ways to predict the internal fields for a given set of conditions. Theoretical methods are also needed to allow extrapolation of observed RFR-related biological effects in animals to effects expected to occur in mankind, since most experiments for studying RFR-related biological effects cannot be performed directly on people for obvious reasons of safety.

Experimental methods are needed to verify theory, to provide additional understanding of the nature of internal fields, and to obtain data for cases in which theoretical calculations cannot be made. Researchers traditionally use a combination of theoretical and experimental techniques to learn as much as possible about dosimetry.

a model of a man would consist of a number of thin planar slabs, each of appropriate size and shape. An important feature of the SIT is that it does not require matrix inversion, in contrast to other numerical methods such as moment methods. This enables the SIT to be used for electrically larger bodies with a large number of unknowns, on the order of 2000 or more. The method has apparently not been used for dosimetry in models of man.

Very Low Frequency and Medium Frequency Techniques--In the frequency range from 20 kHz to 3 MHz, which includes the very low frequency (VLF) and medium frequency (MF) bands, the SARs are very low, even for relatively intense incident fields. Consequently, other factors such as electric shock and RF burn may be more important dosimetric parameters in these frequency bands. Extensive measurements in the VLF and MF bands have recently been made by Guy and Chou.[28] Some similar measurements have been made by Gandhi and Chatterjee.[29]

The quasi-static approximation can be used in the VLF-MF bands because the wavelength is very long compared to the size of the absorbing body. Also, the internal fields in a living subject are small compared to the external fields, and the perturbed external fields and induced charge density are independent of the permittivity of the body tissues. The induced surface charge produces internal currents that are a function of the permittivity, but the total conduction current through any cross section of the body is independent of the permittivity. Measurements in baboons have shown that equipotential planes occur perpendicular to the long axis of the body for E polarization, which means that the internal potential distribution can be predicted from the surface potential distribution. Guy and Chou[28] measured the surface potential distribution on volunteers while applying a known harmless low-level VLF current through the body. From these and geometrical body measurements, they calculated body resistance and SARs for a variety of conditions, such as for exposure of a subject grounded, in free space, and with feet grounded and one hand contacting a large object like a vehicle.

NEAR-FIELD DOSIMETRY

As explained in the Radiation Fields Section, plane-wave analyses are often used in electromagnetic dosimetry because the mathematics are simple in comparison to other cases. However, because many real-life exposures of people to electromagnetic radiation occur in the near fields, being able to calculate the SAR produced by near-field irradiation is very important. As the research progressed in theoretical dosimetry, plane-wave analyses were first developed, providing much useful information and data. Then the work was extended to include the much more complicated near-field analyses. To attempt the near-field analyses without having the basic information provided by the simpler plane-wave analyses upon which to build would have been very difficult.

In contrast to plane waves, near fields are much more complicated in the following respects: 1) the near fields tend to vary more rapidly with space, as explained in the Radiation Fields section, 2) the electric and magnetic field vectors are not necessarily perpendicular for near fields, and 3) the ratio E/H in free space is not necessarily 377. In addition, near fields are not always conveniently characterized by waves; they are often more nonpropagating in nature and are therefore called "fringing fields" or "induction fields." Also, the absorbers in the near field may couple strongly to

in a direction defined by the basis functions. Their formulation, however, has the advantage of only one unknown for each face of the tetrahedral cells. This provides greater modeling power than the cubical cells with pulse functions. That is, the total number of unknowns per volume elements of cells is less with the tetrahedral cells than with cubical cells. For a given number of unknowns, therefore, the tetrahedral-cell model would represent an inhomogeneous object better than the cubical-cell model.

The formulation used by Tsai et al. does represent a field with arbitrary linear variation, but it results in a greater number of unknowns per cell. Because of the linear representation, however, somewhat larger cells can be used. The linear approximation of Tsai et al. also gives a smoother approximation to the fields inside the cells than that of Schaubert et al., which is like a stair-step representation. Both formulations take into account the surface charge density on the surfaces of the cells, which the pulse-function cubical cell model does not. Both Schaubert et al. and Tsai et al. make calculations for homogeneous and layered spheres and compare them to the results obtained from the classical Mie solution. Although comparing accuracies is difficult, the use of linear basis functions promises better calculations of local SAR distribution but at the price of more complexity and more computer time and storage. Using linear basis functions for calculations in models of man will require very large computers.

Iterative Extended Boundary Condition Method--The EBCM described in the previous section has been useful for calculating the SAR in spheroidal models, but the EBCM does not work at frequencies beyond approximately 70 MHz for man models because the matrix equation becomes ill-conditioned. The ill-conditioning occurs because the EBCM represents the EM fields in terms of a spherical harmonic expansion, and this expansion does not fit an elongated object very well at the higher frequencies. Lakhtakia et al.[26] improved the EBCM by incorporating two new procedures. The first is a multiple (instead of one) spherical harmonic expansion. This amounts to dividing the interior of the irradiated object into a number of overlapping spherical subvolumes, expanding the EM fields in each spherical subvolume in a separate spherical harmonic series, and then connecting the expansions by requiring the fields to be continuous in the overlapping regions. This procedure avoids ill-conditioning because the spherical harmonics fit the spherical subregions better than elongated regions. The second new procedure is iteration that begins with an approximate solution (for example, the solution for a perfectly conducting spheroid) and then iterates to obtain the solution for the actual object. The EBCM with these two new features is called the iterative extended boundary condition method (IEBCM). The IEBCM can be used to calculate average SARs for spheroidal models of man up to frequencies of about 400 MHz, which is far greater than the 70 MHz to which the EBCM calculations are limited.

Spectral Iterative Technique--A numerical method quite different from those described above have been developed by Kastner and Mittra.[27] It is called the spectral iterative technique (SIT). The SIT is based on a two-dimensional Fourier transform technique in which the numerical fast Fourier transform (FFT) is used to compute the Fourier transforms. In the SIT, the Fourier transform method for a single arbitrary planar dielectric slab is used repeatedly to compute the SAR for a three-dimensional model. Thus

Very useful data have been obtained by use of the moment method, with calculations ranging up to 600 MHz for man-sized models. Beyond 600 MHz the method is not practical because it requires too much computer memory.

Extended Boundary Condition Method--The extended boundary condition method (EBCM) differs from the moment method in that the EBCM makes use of a spherical harmonic expansion of the incident and scattered EM fields.[20,21] A system of linear equations relating the unknown expansion coefficients of the scattered field to the known coefficients of the incident field is obtained from the boundary conditions and solved by matrix inversion. For man-sized models, the EBCM can be used to obtain SAR data up to about 70 MHz for E polarization.

Some Recent Developments

To help the reader develop a perspective of the work in dosimetry, this section summarizes some of the work that has been done in the last 3 or 4 years. Work described in the previous sections was done prior to that time, much of it in the 1970s.

Moment Method Using Smaller Cells--The use of pulse function in the moment-method solution was shown by Massoudi et al. to result in values for the local distribution of SAR that are of limited accuracy.[22] They showed this by dividing each cubical mathematical cell into smaller cells and recalculating the local SARs. The values for the local SARs did not converge as the size of the cells was made smaller. The reason seems to be that the pulse functions are not adequate approximations to the electric field in each cell because they cannot satisfy the boundary conditions between cells. The whole-body average SAR, on the other hand, did not change appreciably as the cells were subdivided, seeming to indicate that the pulse functions may give acceptable results for whole-body average SARs.

DeFord et al.[23] used the band approximation method for inverting large matrices to calculate SARs in block models having as high as 1132 cells, which is a significantly larger number of cells than the 180 cells typically used previously and requires a significantly greater amount of computer memory and processing time. For whole-body average SAR, their results are about 50% higher for the 1132-cell model than for the 100-cell model, both for homogeneous and inhomogeneous models. Also, the whole-body average SAR for the 1132-cell inhomogeneous model is about twice that for the 180-cell homogeneous model. This trend seems to be consistent with recent experimental results (see the section SOME RESULTS).

Moment Method Using Linear Basis Functions--Since the pulse functions used with the moment-method solution of the integral equations limit the accuracy of the solution, an obvious improvement to try is the use of linear basis functions. Using these functions would be like approximating a function in one dimension by $ax + b$ instead of just by the constant b, which would be like the approximation of a pulse function. Linear basis functions have been used by Schaubert et al.[24] and by Tsai et al.[25] In both cases, tetrahedral cells were used instead of the cubical cells used in block models with the pulse functions. The basis functions used by Schaubert et al. do not accurately represent a field with arbitrary linear variation, but only linear variation

of humans and animals, as given in the second edition of the Radiofrequency Radiation Dosimetry Handbook.[1] The result is a simple formula that can be used to calculate the SAR for E polarization as a function of frequency for prolate spheroidal models ranging in size from rats to humans. The equation is simple enough to be used with a hand calculator, and the accuracy is a few percent.

Similar techniques have been used to obtain information for models of humans standing on or near ground planes,[15] such as a man wearing shoes and standing on perfectly conducting ground. The main effect of the ground plane is to shift the resonant frequency.

Numerical Techniques

Numerical techniques that are characterized by the solution of large matrix equations are described here.

Moment Method--A numerical technique called the moment method has been used to calculate both average and local SARs in block models of man.[16-19] This method is based on the solution of an integral equation in which the electric field in each mathematical cell of the model is represented by a pulse function (the electric field has a constant value everywhere inside the mathematical cell). Several block models have been used with this method. The one used by Hagmann et al. is shown in Fig. 4. It was designed by choosing the cubical cells to form the volume and shape most closely resembling an average man.

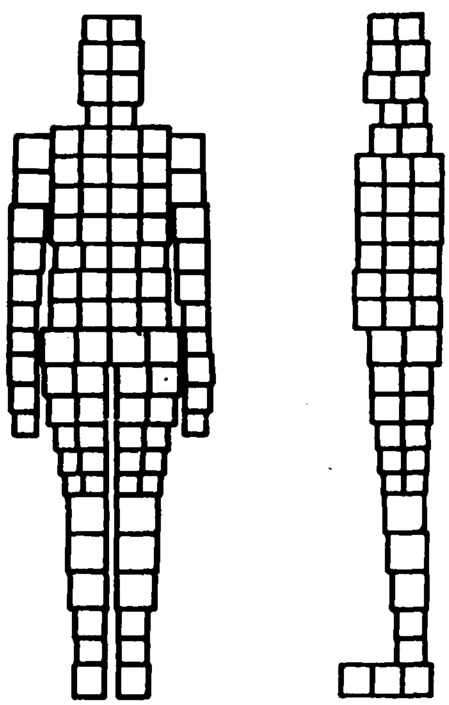

Fig. 4. The block model of man used by Hagmann et al.[18]

Long-Wavelength Analyses--Extensive use has been made of an approximation with spheroidal and ellipsoidal models that is valid when the wavelength is long compared to the size of the model.[8,9] In this method, Maxwell's equations are expanded in a power series in k, the free-space propagation constant. Approximations are then made to obtain simpler equations that are valid in the low-frequency range. These equations are easier to solve than Maxwell's equations because they require only solutions to Laplace's equation instead of the solution to wave equations. The approximation is valid for man-sized models up to about 30 MHz.

Since these spheroidal models do not include features such as arms and legs, the analysis does not provide much useful information about SAR distribution. These approximate calculations, however, have provided much useful information about average SAR. For example, the polarization effects shown in Fig. 1 were first calculated by the long-wavelength approximation for prolate spheroids. The long-wavelength analyses are useful because they provide an easy way to calculate the SAR at low frequencies for any size spheroid, because they provide important insight into the qualitative nature of SAR characteristics, and because they provide a good check for numerical techniques at lower frequencies.

Cylindrical Models--At first it was difficult to calculate average SARs in the range of frequencies from about 400 MHz to 7 GHz. In this range, numerical techniques cannot be used because the wavelength is short enough that the matrices are extremely large and difficult to invert, yet the frequency is still low enough that the short-wavelength approximations are not valid. Cylindrical models do, however, provide useful information in this frequency range.[10]

As shown in Fig. 2, the results obtained from the cylindrical model agree well with those obtained from other models in the transition region near 400 MHz. Standard electromagnetic techniques based on classical electromagnetic equations are used for calculation in the cylindrical model. Although the solution is well known and straightforward, at the high end of the frequency range the technique is limited by difficulties in calculating the higher order Bessel functions of large complex argument.

Since the cylindrical model is infinitely long, it cannot be used for K polarization; however, it has provided much useful information for E polarization and H polarization.

Spheroidal Wave Functions--Another analytical technique that has been used is the direct solution of Maxwell's equations in spheroidal coordinates.[11] Although a formal solution has been obtained, the numerical calculation of the SAR is so difficult that little useful information has been obtained for RFR dosimetry in human models.

Empirical Techniques--Several empirical relations for describing the SAR have been developed.[12,13] These relations are based on the characteristic behavior of the SAR for E polarization as shown in Fig. 2, and they were obtained simply by finding equations that would reproduce the SAR-versus-frequency curves. Durney et al.[14] did this by obtaining the least-square best fit of the relation to all the data calculated for prolate spheroidal models

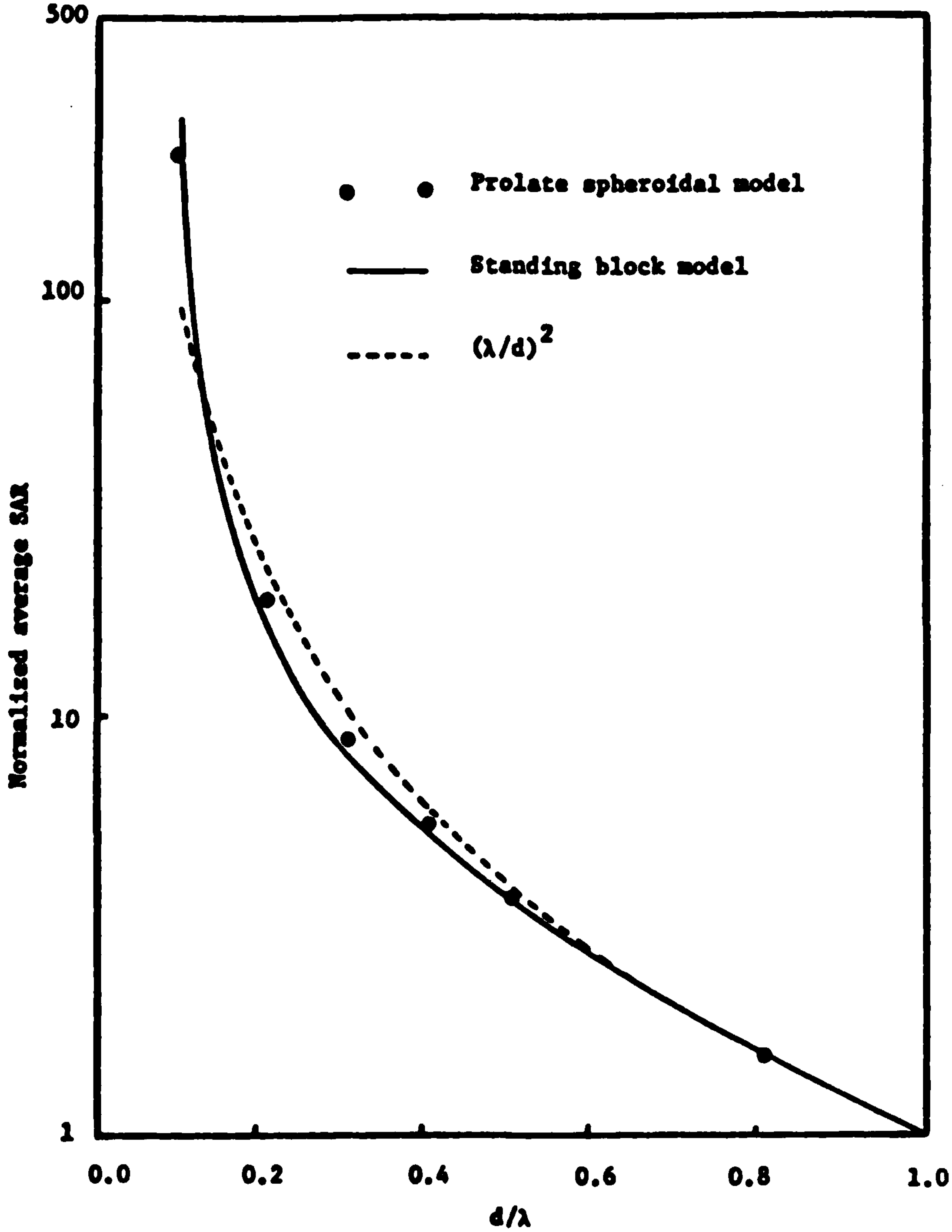

Fig. 3. Normalized average SAR in spheroidal models compared to block models,[3] both irradiated by a short electric dipole.
d is the distance from the dipole
λ is the wavelength

representations of the human body in the sense that they do not represent shapes such as those of arms and legs well enough. Therefore, the method gives little useful information about local SAR, although it has furnished very useful information about average SAR. As shown in Fig. 3, the average SAR in spheroidal models has been found to be nearly the same as that in block models.[3] This is very fortuitous since the approximate methods are much easier to use than the more complicated numerical techniques. Numerical techniques, however, can furnish much better information about local SAR.

For frequencies beyond 400 MHz, primarily two techniques have been used for calculating the SAR. One is the analytical solution of Maxwell's equations for cylindrical models. This technique is useful when the wavelength is short compared to the length of the body, which occurs above about 400 MHz for man-sized models. Because of computational difficulties, it can be used only up to about 7 GHz. Above 7 GHz another approximation, based on geometrical optics techniques, is useful. In this approximation, the wavelength is assumed to be very short compared to the size of the body, which allows the incident radiation to be described by rays. An additional approximation is made that the internal absorption is high enough that the rays are not internally reflected but are completely absorbed.

Qualitative explanations for the characteristics of the curves shown in Fig. 2 are given in the section QUALITATIVE EXPLANATIONS OF ABSORPTION CHARACTERISTICS. The theoretical methods used to obtain the curves in Fig. 2 are described in more detail in the remainder of this section in terms of two main categories: analytical techniques and numerical techniques.

Analytical Techniques

The techniques described here are called analytical techniques because, in contrast to numerical techniques, they consist of some solution to Maxwell's equations that does not usually require a large matrix inversion. Numerical techniques based on large matrix inversions will be described later.

Planar and Spherical Models--Because of their mathematical simplicity, planar and spherical models were used in early work to calculate the SAR.[4-6] While planar models have the advantage of being the simplest mathematically, the information obtained from planar model analyses is useful mostly for some qualitative understanding; the data do not represent absorption by human bodies very well. The sphere[6] is a better model, although it is still quite limited in representing the shape of the human body and is more difficult to analyze than planar models.

Even though the analyses of planar and spherical models were very limited in terms of providing useful data, they did provide important first steps in understanding theoretical dosimetry. The spherical model[6] showed a resonance similar to that of the K polarization in Fig. 2, but naturally could not show the polarization effects. Analyses of multilayered spherical models[7] have shown that the resonance properties are significantly different for the layered models than for homogeneous models. The multilayered spherical models have primarily been used for investigations of absorption in the human head.

and other animals has been obtained by combining results from several techniques. As shown in Fig. 2, several kinds of models have been used, as well as several methods of computation.

Numerical techniques have been used up to frequencies of about 600 MHz. Beyond this frequency, numerical techniques have not been used because they require excessive amounts of computer storage. Numerical techniques are generally characterized by the solution of large matrix equations obtained either from a discrete form of Maxwell's equations or from simultaneous equations for coefficients of series solutions. In the matrix equation, a matrix element corresponds to the field intensity in a mathematical cell in the body. Since the field intensity in each cell is often assumed to be constant throughout the volume of the cell, the mathematical cells must be smaller at high frequencies where the wavelength is smaller and the spatial variation in the fields correspondingly more rapid. Thus at high frequencies a large number of mathematical cells is required, making the matrix inversion very difficult.

In the lower frequency range an analytical approximate solution of Maxwell's equations is useful. This approximation is valid when the wavelength of the incident radiation is large compared to the size of the body, which is up to frequencies of about 30 MHz for man-sized models. The technique is limited to spheroidal and ellipsoidal models, which are not good

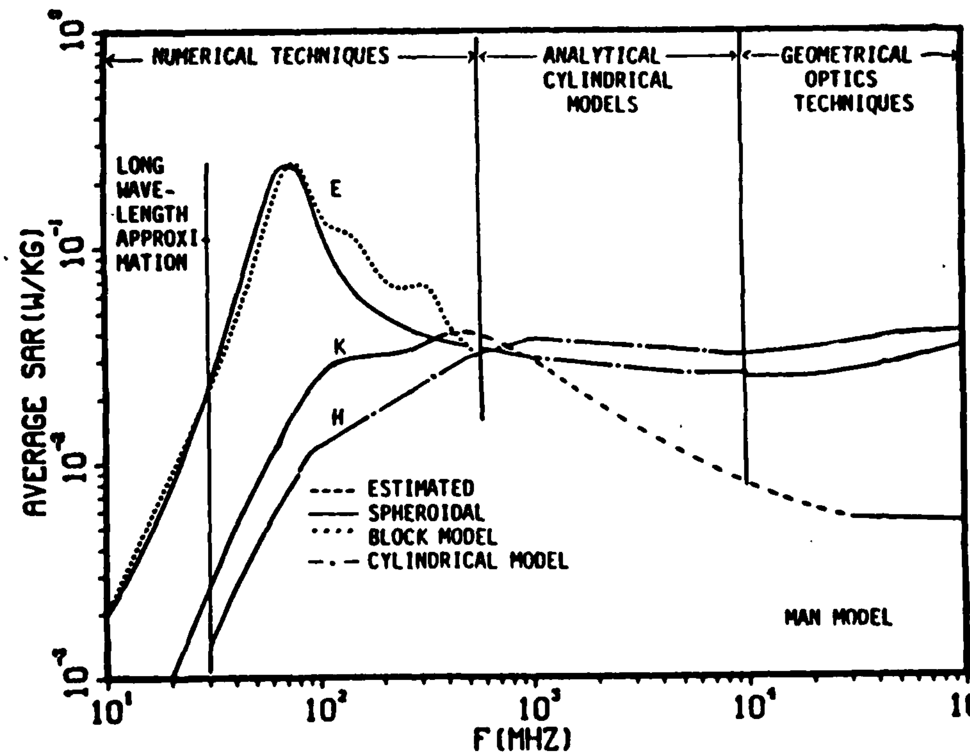

Fig. 2. Average SAR for models of an average man irradiated by an EM plane wave of 1-mW/cm^2 power density. E, K, and H designate polarizations in which the incident electric field vector, propagation vector, and magnetic field vector, respectively, are parallel to the long axis of the body. The various methods used to make the calculations are shown.

discussion in this paper. Polarization is important because the SAR depends strongly upon it, as explained in the section QUALITATIVE EXPLANATIONS OF ABSORPTION CHARACTERISTICS.

Measurements

Two basic techniques are used to measure internal fields. One is to use an E-field probe designed for use inside an object. These probes provide a direct measurement of $\underline{E}_{in}$, which can then be used in equation 2 to calculate the SAR if the value of ε'' is known. The main difficulty with internal E-field probes is getting enough sensitivity in a small enough probe. The problem is especially difficult at the lower frequencies, where the wavelength is so long that a physically small probe is very short compared to a wavelength and consequently is insensitive. Another problem is the difficulty in designing a probe so that it reads independently of the permittivity of the material in which it is placed. Some good probes have been designed for use in biological material, however, and better ones are being developed.

A second basic method is to measure temperature rise in the body. Johnson and Guy[2] showed that the SAR can be calculated from the temperature increase without knowing the detailed heat transfer characteristics of the body if the incident radiation is strong enough to produce a temperature rise that is linear with time. This is possible because thermal diffusion is negligible if the temperature rise is linear. The equation they derived is:

$$\mathrm{SAR} = \frac{4.186\ pc\ \Delta T}{\Delta T}$$

where

SAR is in W/cm^3.

p is the mass density in g/cm^3.

c is the specific heat of the tissue in cal/g°C.

ΔT is the temperature change in °C

Δt is the time of exposure in seconds.

Several temperature probes that will not perturb internal fields have been developed and can be used to measure temperature rise during RFR. Whole-body calorimetry can also be used to measure the average SAR in small animals.

THEORETICAL METHODS

Figure 2 shows the average SAR as a function of frequency for models of an average man irradiated by an EM plane wave for the three polarizations. A combination of techniques has been used in theoretical dosimetry calculations because the problems are so complex that no one technique itself is adequate. Extremely important information about the absorption characteristics of humans

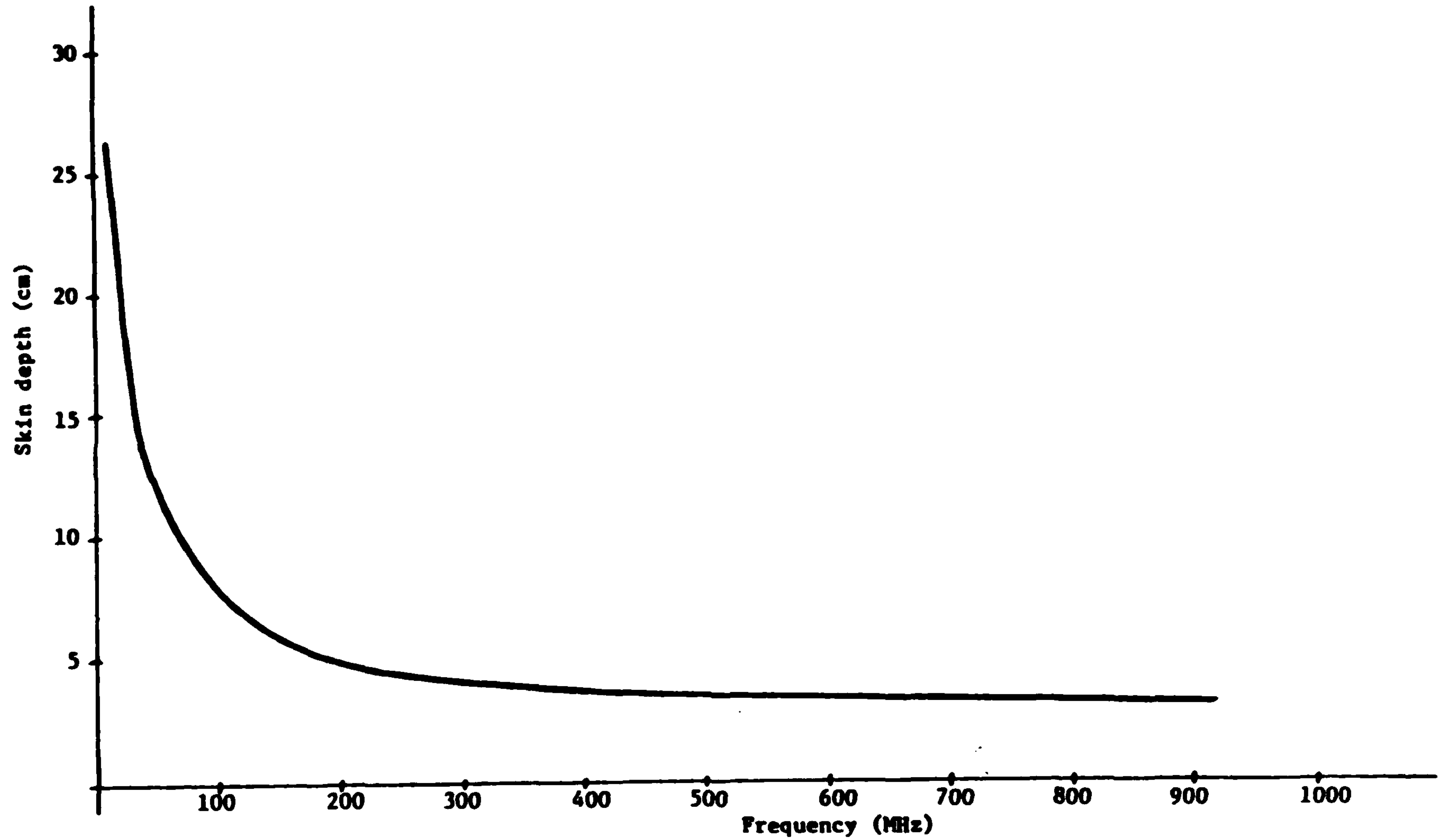

Fig. 1. Skin depth as a function of frequency for an EM plane-wave incident on a dielectric half-space having a permittivity two-thirds that of muscle tissue.

in dosimetry. It is important to note, however, that the temperature of the body is not necessarily proportional to the SAR, since temperature is the result of all the thermal properties of the body in addition to the SAR. Although regions of intense localized SAR are sometimes referred to as "hot spots," this nomenclature is not precise because the temperature may or may not be correspondingly high at that point, depending on the heat transfer characteristics of the body.

From equation 2 we see that for a given E_{in} and ω, the SAR is directly proportional to ε''. Thus a body with a higher ε'' is said to be more absorbing, or more lossy, than a body with a lower ε''. Generally speaking, ε'' tends to be higher for "wetter" materials and lower for "drier" materials. For example, the ε'' for dry paper is very low, while that for wet paper is relatively high. In a microwave oven wet paper will heat up until it dries out and will then no longer heat. In biological materials, bone and fat are not as lossy as muscle.

Penetration and Frequency Characteristics--In dosimetry, an important characteristic is the dependence of absorption on frequency. This dependence is very complex, but some simple characteristics provide adequate qualitative understanding of dosimetry. The depth of penetration of RFR in a lossy medium is a strong function of both frequency and permittivity. For a given permittivity, low-frequency radiation penetrates deeper than high-frequency radiation; thus, high-frequency radiation characteristically produces only surface heating. At a given frequency, RFR penetrates deeper into materials with low permittivity than those of high permittivity. These two characteristics can be made clearer by reference to Fig. 1, which shows the skin depth of a plane wave incident on a planar dielectric half space, as a function of frequency. Skin depth is defined as the distance at which the EM fields have reduced to e^{-1} (0.368) of their value at the surface. This corresponds to the power absorption being e^{-2} (0.135) of the surface value. The plot in Fig. 1 is for material with a permittivity two-thirds that of muscle, which is an average permittivity for the human body. Since the skin depth depends on both ε' and ε'', and since both ε' and ε'' increase as frequency decreases, the skin depth does not increase as fast when the frequency decreases as it would if the permittivity did not depend on frequency.

Since the curve in Fig. 1 is for a planar dielectric half space, it does not tell us much about the penetration depth in man-sized models at lower frequencies; but it does give important qualitative information.

Polarization--An important factor in dosimetry is polarization, which is the orientation of the EM field vectors with respect to the body. For plane wave fields, the polarization is designated by which of the vectors $\underline{E}$, $\underline{H}$, or $\underline{k}$ is parallel to the long axis of the body, where $\underline{k}$ is a vector in the direction of propagation. If the $\underline{E}$ field is parallel to the long axis of the body, the polarization is called E polarization. Similarly, H and K polarization are when $\underline{H}$ and $\underline{k}$, respectively, are parallel to the long axis of the body.

These three definitions of polarization are sufficient for bodies of revolution about the long axis, such as a cylinder and prolate spheroid (like an egg). The human body, however, is not a body of revolution, and more detailed definitions of polarization have been made[1] but are not necessary for

2. E fields induce electric dipoles in atoms and molecules. This is called polarization. The friction associated with polarization results in "heating" the material, which represents a transfer of energy to the material from the E field.

3. E fields align electric dipoles already existing in the material. The friction associated with this alignment results in an energy transfer to the material.

These three energy transfer mechanisms (also often called loss mechanisms because they represent energy lost from the E field to heat the body) are traditionally described by material properties called permittivity and conductivity. For EM fields that vary sinusoidally with time, one property, complex permittivity, describes all the loss mechanisms. The complex permittivity is given by

$$\varepsilon = \varepsilon_0(\varepsilon' - j\varepsilon'') \tag{1}$$

where ε_0 is a constant called the permittivity of free space, ε' is the real part of the relative complex permittivity, or dielectric constant, ε'' is the imaginary part, and $j = \sqrt{-1}$. The ratio $\varepsilon''/\varepsilon'$ is called the loss tangent. Many tables list both ε' and the loss tangent. Other tables list only ε' and σ, the dc conductivity, which is related to ε'' by $\sigma = \varepsilon''/\omega\varepsilon_0$, where ω is the radian frequency.

Specific Absorption Rate (SAR)--The rate of energy transfer to a material is commonly described in dosimetry by the specific absorption rate (SAR). The SAR is defined as the time rate of energy transfer to the body, per unit mass. The average SAR is the total energy transferred to the body per unit time divided by the total mass of the body. The local SAR is the rate of energy transferred to an infinitesimal volume at a point in the body, divided by the mass of the infinitesimal volume. For sinusoidal fields, the SAR at a given internal point is:

$$\mathrm{SAR} = \frac{1}{\rho}\,\omega\varepsilon_0\varepsilon'' E_{in}^2 \ \mathrm{W/kg} \tag{2}$$

where

ρ is the mass density in kilograms/meter^3.

ε_0 is the permittivity of free space in farads/meter.

ε'' is the imaginary part of the relative complex permittivity.

ω is the radian frequency. ($\omega = 2\pi f$, where f is the frequency in hertz.)

E_{in} is the magnitude of the internal electric field at the point in RMS volts/meter. The internal field is not equal the incident field.

Since the SAR is the mass normalized rate of energy transfer, it is equivalent to the mass normalized power transferred to the body and is commonly called absorbed power density. Since heat generated in a body is directly proportional to the absorbed power, the SAR is often of major interest

crests of the water wave. To understand the meaning of EM wave frequency, think of the waves rollin in on the beach. The frequency of a water wave is the number of crests passing any given point in 1 s. The frequency of an EM wave is analogous; it is the number of peaks of E or H that pass a given point in space in 1 s.

There are two general classes of radiation fields: near fields and far fields. The mathematical expressions for EM fields contain terms like $1/r$, $1/r^2$, $1/r^3$, ..., where r is the distance from the source. In a region "far" from the source, the terms $1/r^2$, $1/r^3$ ...become negligible compared to the $1/r$ term, and the fields are said to be far fields. When the higher order terms in r cannot be neglected, the fields are called near fields. The near fields vary more rapidly with distance than do the far fields and are generally more difficult to handle mathematically.

One common type of far-field wave is a spherical wave, in which the wavefronts form spheres. If the radius of the spherical wavefront is large enough, the spherical wave approximates a plane wave. A plane wave is a mathematical model; plane waves do not actually occur physically. In plane waves, the wavefronts are planes and the magnitudes of both E and H are constant throughout a given plane, which, of course, is not physically possible. The plane wave, however, is a very useful model because it is relatively simple mathematically and it does form a useful approximation to some far fields. The plane wave has been widely used in dosimetry to provide important understanding as well as approximate results.

The defining characteristics of a plane wave are:

1. The wavefronts are planar.

2. $\underline{E}$ and $\underline{H}$ are perpendicular to each other and are both perpendicular to the direction of propagation.

3. In free space, $E/H = 377$ ohms, which is called the wave impedance.

Another important feature of plane waves is that the radiation fields can be completely specified by 1) the orientation of the $\underline{E}$ field (or the $\underline{H}$ field, 2) the direction of propagation, and 3) the power density. The time-averaged power density in a plane wave is given by

$P = EH = E^2/377$ (in W/m²) (if E is in RMS V/m)

where E and H are the magnitudes of the electric- and magnetic-field vectors respectively.

Absorption Characteristics

Material Properties--Electric fields transfer energy to material bodies by three principal mechanisms:

1. $\underline{E}$ fields give kinetic energy to electrons that are not tightly bound to any one atom. These are called free electrons.

Theoretical methods consist basically of solving Maxwell's equations, the fundamental basis of electromagnetic theory, for the particular absorber and radiation fields of interest. This includes representing both the actual absorber (usually an animal or a person) and the incident radiation fields by mathematical models. Since the mathematical models are never completely accurate representations of either the absorber or the incident fields, the calculated internal fields are always only approximations to any real physical values. And the better the model is, the more complicated the calculations usually are.

Experimental methods typically consist of techniques for measuring either the internal electric field or the temperature rise at internal points. Under certain conditions, both the internal fields and the energy absorbed can be calculated from the internal temperature rise.

Some basics of electromagnetics will be described first; then theoretical methods, in two groups--analytical and numerical. Work in near-field dosimetry will be described next, followed by some experimental results. Finally, some qualitative explanations of absorption and a summary will be given.

SOME BASICS OF ELECTROMAGNETICS

As explained in any of the many books on the subject, the framework of electromagnetics is Maxwell's equations, which describe the relations between the electric ($\underline{E}$) field, the magnetic ($\underline{H}$) field, and the sources--charge and current--that produce these fields. Other auxiliary questions describe the interaction of these fields with materials. Since Maxwell's equations are very difficult to solve, a variety of special techniques have generally been used to solve them for special conditions. For example, when the frequency of the radiation is low enough that the wavelength is very long compared to the size of the objects, Maxwell's equations may be approximated by the equations of <u>circuit theory</u>. For extremely high frequencies, where the wavelength is very small compared to the size of the objects, Maxwell's equations are approximated by the equations of <u>optics</u>. In the range where the wavelength is about the same size as the object, the techniques of <u>microwave</u> theory apply.

A combination of techniques and models has been used also in dosimetry. As a prelude to the description of these techniques in the next section, some of the fundamentals of electromagnetics are explained now.

Radiation Fields

The radiation fields are those to which the object is exposed and which would be measured in the absence of the object. Radiation fields are usually categorized according to frequency, the magnitudes of $\underline{E}$ and $\underline{H}$, and their spatial variation, as described below.

Typically, radiation fields are also described as propagating waves. For many purposes, electromagnetic (EM) waves can be thought of as being like a water wave. The maximum values of E and H are like the crests of the water wave. The <u>wavelength</u> of the EM wave is analogous to the distance between the

the electromagnetic source and change the radiation produced by the source. All these factors combine to make the mathematical formulation of near-field absorption much more difficult than that of plane-wave absorption.

Another important complicating factor is that the absorption produced by near fields cannot be conveniently normalized to the incident power density, as it can be for plane waves. The incident fields for far fields can be fully characterized by just two quantities: the incident power density and the orientation of the fields with respect to the absorber. For near fields, however, no such standardization is possible because the $\underline{E}$ and $\underline{H}$ vectors are not necessarily perpendicular, and no parameter corresponds to the convenient power density that is so easily specified for far fields. This makes near-field dosimetry much more difficult to generalize, since calculations for each near-field source must be made separately. It is therefore difficult to compare the absorption characteristics produced by one source with those of another. On the brighter side, though, it turns out that the same qualitative explanations of absorption apply for both near fields and far fields, as explained later. A compilation of near-field dosimetric techniques and data is contained in the third edition of the Radiofrequency Radiation Dosimetry Handbook.[30]

The work in near-field theoretical dosimetry began with simple models and simple sources. The SAR produced in spheroidal and cylindrical models irradiated by the near fields of simple sources, such as short electric dipoles and small magnetic dipoles, have been calculated using the long-wavelength approximation explained in the Long-Wavelength Analyses section.[31] In this approximation the incident fields are averaged along the axis of the spheroid, and the average is used in the long-wavelength approximate equations developed for plane-wave analyses. The results obtained are surprisingly close to those calculated by more accurate methods. The long-wavelength approximation is very useful for near fields because the calculations are easy to make and the equations provide valuable insight.

The EBCM has also been used for near-field calculations.[32] The SARs produced in spheroids irradiated by short electric dipoles, small loops, and small-aperture fields have been calculated. Work is also under way to calculate the SAR in spheroids produced by the irradiation of larger aperture sources.

Calculations of the SAR in infinite cylindrical models of the human body have also been made. Techniques used were similar to those for plane-wave irradiation, but the resulting mathematical formulation was much more complicated.

Another technique that has been used is expanding the incident near fields in terms of a spectrum of plane waves, then calculating the average SAR for each plane-wave component by techniques previously used in block models of man.[33] Again, the calculations of the near-field SAR are much more complicated than those for plane-wave irradiation.

SOME RESULTS

Extensive SAR data are given in the Radiofrequency Radiation Dosimetry Handbooks. The second edition contains primarily SAR data for plane-wave

irradiation. The third edition contains the available data for near-field irradiation. The fourth edition, which is scheduled for release in 1985, will include material from previous editions along with the most recent work. Since these extensive compilations of data are available, only examples of dosimetry results are given in this paper.

Figure 2, which shows the SAR and the function of frequency for plane-wave irradiation of a model of an average man, illustrates how the SAR changes with polarization of the incident radiation. The strong resonance effect for the E polarization is also evident. A less pronounced resonance occurs with K polarization, and essentially no resonance with H polarization. It is interesting to note that the block-model curve in Fig. 2 also shows smaller resonances that are produced by the other parts of the body, such as the head and arms. These minor resonances, of course, do not appear in the results calculated for spheroidal models.

Figure 5 shows a comparison between the SAR characteristics for an average man and a medium rat. The resonances, which are markedly different for the two models, occur at frequencies for which the length of the body is approximately four-tenths of a wavelength. A very different internal field pattern would occur in a man at a given frequency than in a rat at that same frequency. More is said about this in the next section.

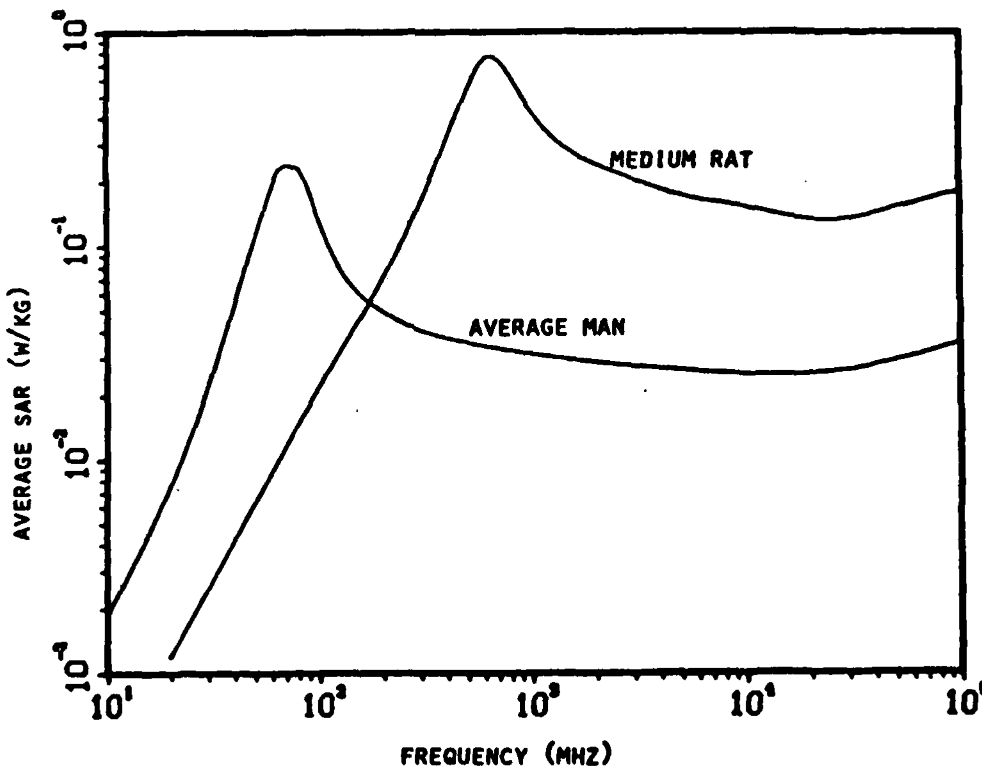

Fig. 5. Average SAR for prolate spheroidal models of an average man and a medium rat for E polarization, for an incident plane-wave power density of 1 mW/cm^2 [1].

The effects of a ground plane on the average SAR for man models is shown in Fig. 6. The main effect of the ground plane is to lower the resonant frequency. Because the electric image of the man in the ground plane makes the length of the body appear to be twice as long as it would be in free space, the resonant frequency would be approximately half that of the body in free space.

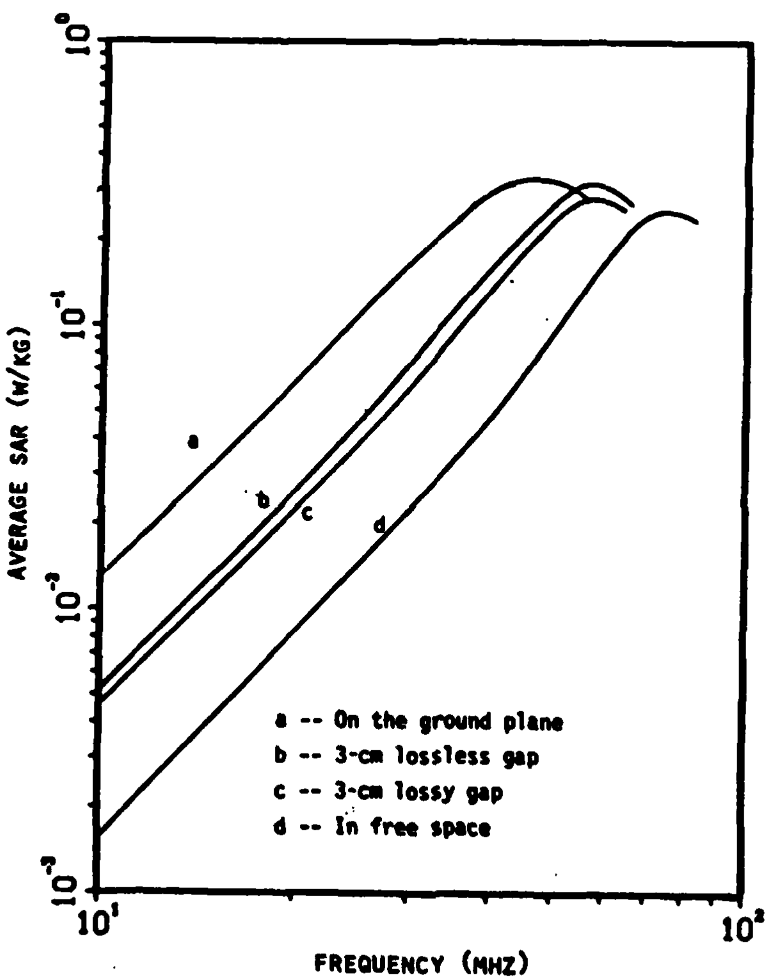

Fig. 6. **Average SAR for an average man separated from a perfect ground plane by a 3-cm gap, both with and without loss.[1] Curves for the man standing on the ground plane and in free space are shown for comparison.**

A comparison between calculated values for spheroidal models and some earlier experimental values in saline figurines is shown in Fig. 7. Another comparison between block-model calculations, VLF-MF measurements, and thermographic measurements is shown in Fig. 8. Other experimental data are summarized in the Radiofrequency Radiation Dosimetry Handbook.[1,30] The experimental values in Fig. 7 are quite close to the measured values. The measured values in Fig. 8, though, are a factor of 2 or more higher than the calculated values for the block model. Hill[34] obtained similar results in measurements on human volunteers. His measured SAR values at frequencies in the 10-30-MHz range were about a factor of 2 greater than values calculated for spheroidal and block models. Hill proposed that the spheroidal models should be chosen on the basis of the ratio of the major axis to the minor axis, rather than on the basis of major axis and mass as usually has been done. He showed that thinner spheroids give results closer to measured values.

As mentioned in the section Moment Method Using Smaller Cells, the calculations for SAR distribution using the block model and moment method with pulse basis functions have given inaccurate results, but it was thought that calculations for average SAR using this method gave good results. The experimental data in Fig. 8 and Hill's results seem to indicate that even the calculations for average SAR in the block model are not as good as supposed. This is reinforced by the fact that DeFord et al.[23] found the average SAR for the 1132-cell inhomogeneous block model to be about twice that for the 180-cell homogeneous block model. Further refinements of the models will probably bring the calculated and measured values even closer together.

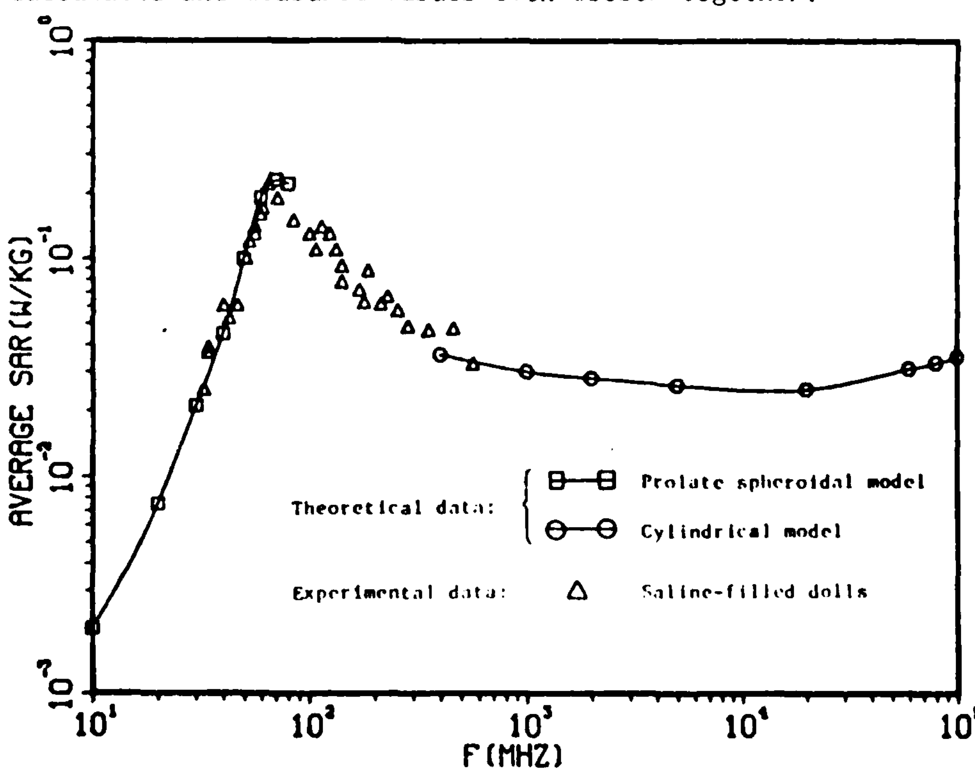

Fig. 7. Calculated and measured values of the average SAR for models of an average man, E polarization.[1] Incident power density is 1 mW/cm^2.

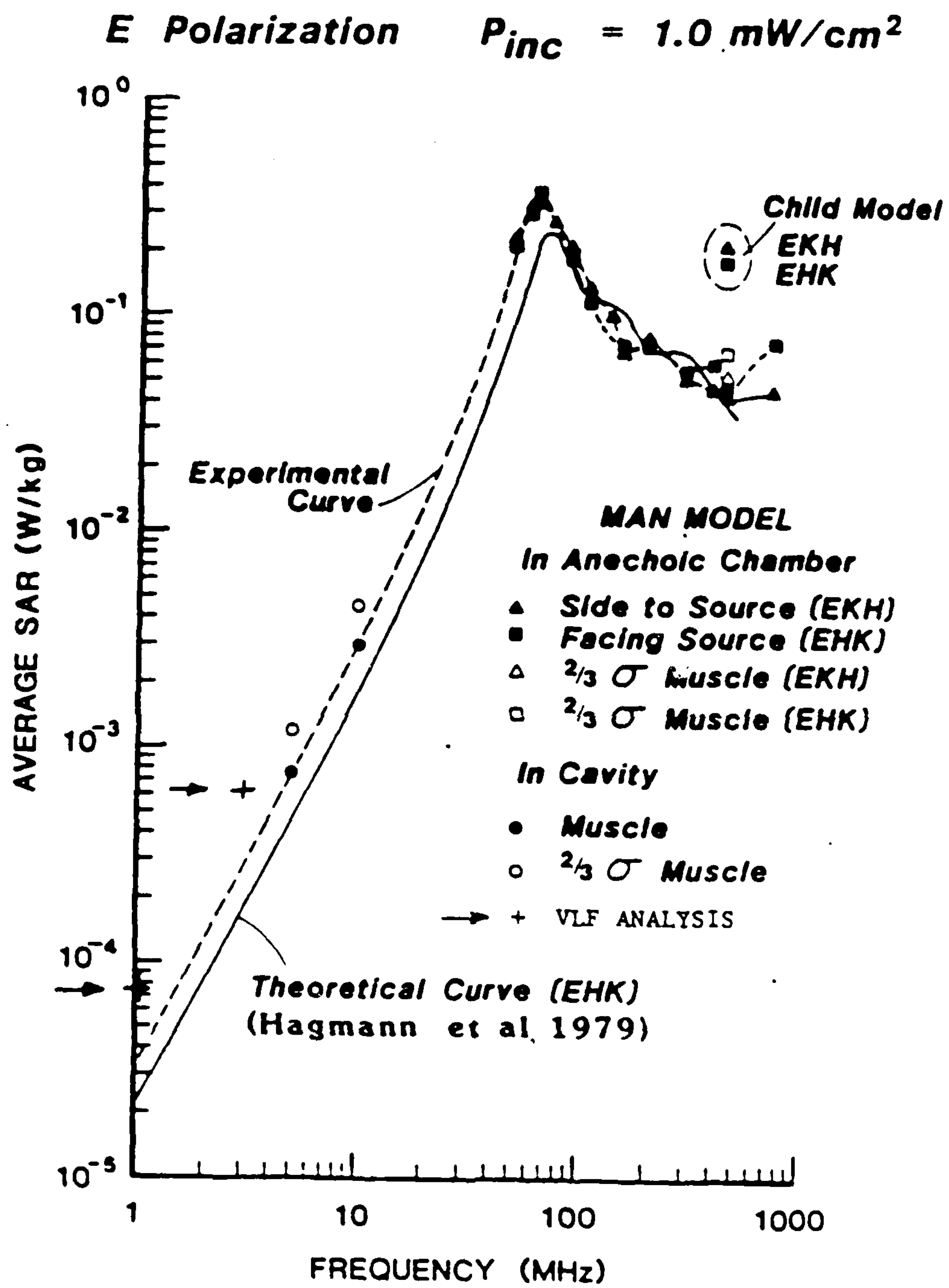

Fig. 8. Comparison of theoretical and experimentally measured whole-body average SAR for realistic man models exposed at various frequencies. The experimental curve is measured results in scaled human-shaped models at simulated VLF frequencies, using thermographic techniques.[28]

Figure 9 shows the average SAR in a spheroidal model of an average man irradiated by a short electric dipole at 200 MHz as a function of the distance between the dipole and the spheroid. Note that the SAR does not increase as fast as the inverse distance squared (as might be expected from the 1/r variation of the far fields), which would correspond to a $1/r^2$ variation in the incident power density of the far fields. One might expect that the SAR increase in the near fields would be greater than in the far fields since the near fields vary faster than 1/r. The reason that the SAR does not increase as fast as inverse distance squared is explained in the next section in terms of the incident near-field variation. Similar behavior has been found in measurements of the average SAR in spheroidal models.[35]

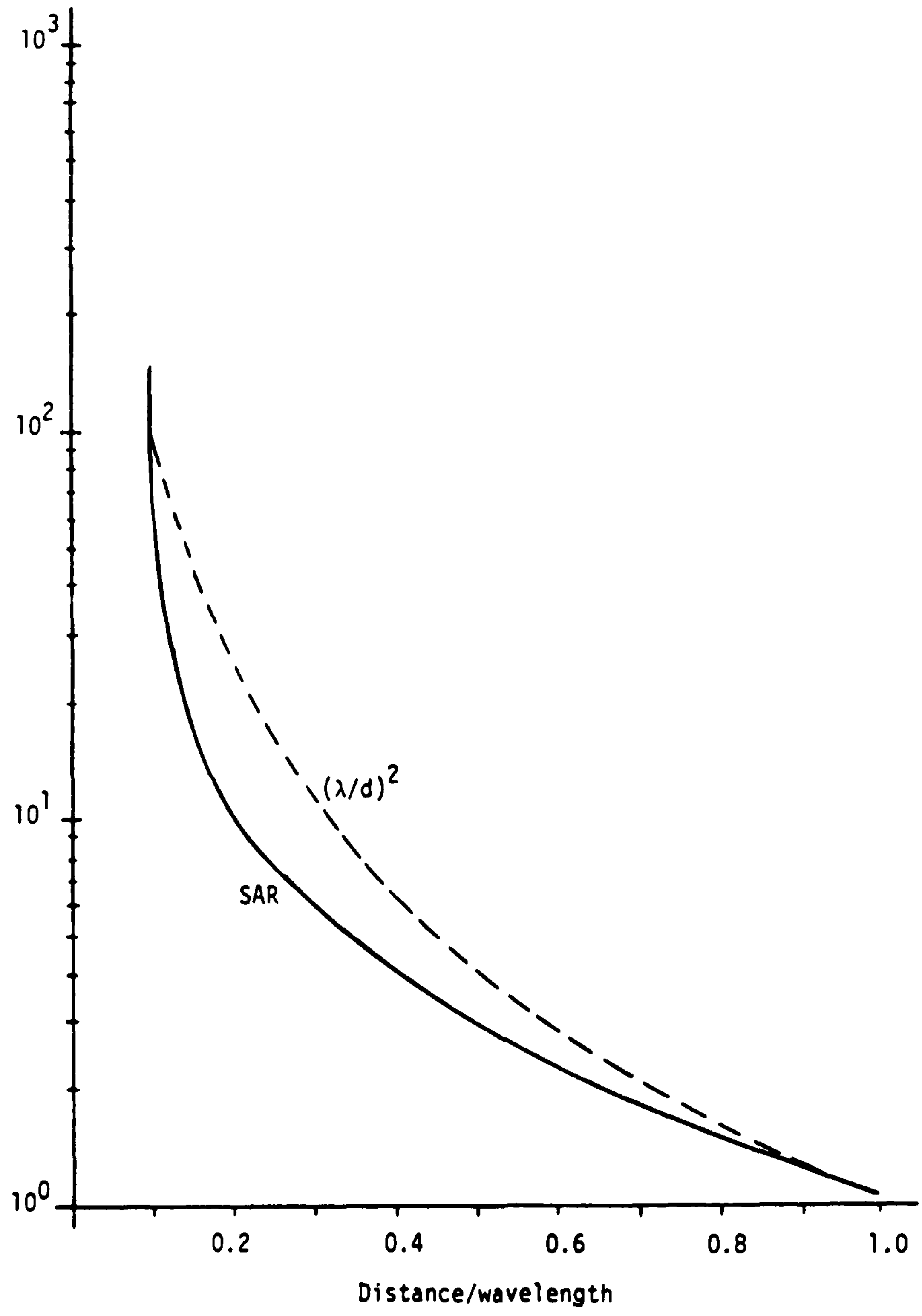

Fig. 9. Calculated values of normalized SAR and $(\lambda/d)^2$ for a spheroidal model of an average man irradiated by a short electric dipole for E polarization at 200 MHz.[1]

d is the distance between the dipole and spheroid

λ is the wavelength of irradiation

QUALITATIVE EXPLANATIONS OF ABSORPTION CHARACTERISTICS

This section describes two qualitative principles that can be used to predict relative average SAR values, and gives some examples of qualitative explanations based on these principles.

Qualitative Principles

At the lower frequencies, the internal electric fields can be thought of as being generated by the incident $\underline{E}$ and $\underline{H}$ separately. That is,

$$\underline{E}_{in} = \underline{E}_e + \underline{E}_h \qquad (3)$$

where

$\underline{E}_e$ is the internal electric field caused by $\underline{E}_{inc}$, the incident $\underline{E}$ field.

$\underline{E}_h$ is the internal electric field caused by $\underline{H}_{inc}$, the incident $\underline{H}$ field.

$\underline{E}_{in}$ is the total internal electric field in the body.

At the lower frequencies, $\underline{E}_e$ and $\underline{E}_h$ can be calculated separately from $\underline{E}_{inc}$ and $\underline{H}_{inc}$ and added to obtain $\underline{E}_{in}$, as given in equation 3. This is not true at higher frequencies, where $\underline{E}_e$ and $\underline{E}_h$ cannot be separately attributed to $\underline{E}_{inc}$ and $\underline{H}_{inc}$, respectively, since E and H are coupled together by Maxwell's equations. The general concepts based on equation 3, however, do seem to have some validity at higher frequencies, sometimes even up to resonance.

The following two principles can be used to predict the relative values of $\underline{E}_{in}$:

1. $\underline{E}_e$ is <u>stronger</u> when $\underline{E}_{inc}$ is mostly <u>parallel</u> to the boundaries of the object, and <u>weaker</u> when $\underline{E}_{inc}$ is mostly <u>perpendicular</u> to the boundaries of the object.

2. $\underline{E}_h$ is <u>stronger</u> when $\underline{H}_{inc}$ intercepts a <u>larger</u> cross section of the object, and <u>weaker</u> when $\underline{H}_{inc}$ intercepts <u>smaller</u> cross section of the object.

Figure 10 shows some examples of qualitative evaluations of internal fields based on these principles. For simplicity, only simple objects are used for illustration, but the principles apply to more complicated shapes like the human body.

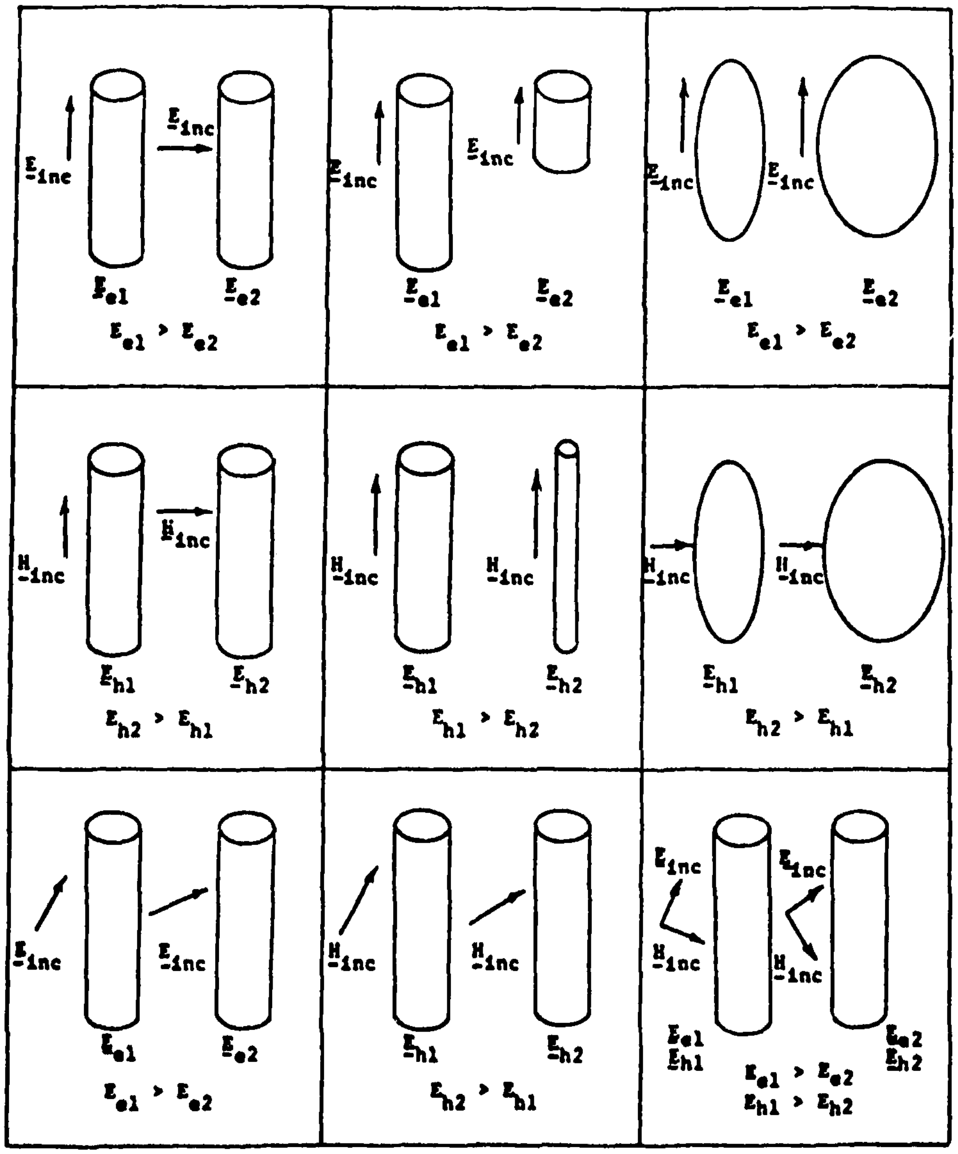

Fig. 10. Qualitative evaluation of the internal fields based on qualitative principles.[1] $\underline{E}_e$ is the internal electric field generated by $\underline{E}_{inc}$, the incident E field; and $\underline{E}_h$ is the internal electric field generated by $\underline{H}_{inc}$, the incident H field.

Explanation of Polarization Effects

Figure 11 illustrates the qualitative explanation of the difference in average SAR shown in Fig. 2 for the three polarizations. For frequencies below resonance, the average SAR for E polarization is the greatest because both $\underline{E}_e$ and $\underline{E}_h$ are strong. The SAR for H polarization is lowest because both $\underline{E}_e$ and $\underline{E}_h$ are weak. The average for K polarization lies between that for E polarization and that for H polarization because $\underline{E}_e$ is weak but $\underline{E}_h$ is strong, thus the two qualitative principles very nicely explain why the SAR is a strong function of the polarization. Other similar qualitative explanations can be used to predict whether the average SAR will be large or small for a given set of conditions.

Explanation of Near-Field SARs

Similarly, the qualitative principles can be used to explain near-field absorption characteristics. Figure 12 shows the same information as Fig. 9, along with information about the electric field. Note that $|E|^2$ is less than $(\lambda/d)^2$ but follows along nearly parallel with it. The change in $|E|^2$ does not explain why the average SAR increases more slowly than $(\lambda/d)^2$ until it rises suddenly between $\lambda/d = 0.2$ and 0.3 and then rapidly increases above $(\lambda/d)^2$ for λ/d less than 0.2. The explanation is found in the change of the orientation of the $\underline{E}$ field with respect to the spheroid, as described by α, the angle between $\underline{E}$ and the major axis of the spheroid. Note that α is increasing from $\lambda/d = 1$ to about 0.25, where it suddenly begins to decrease. As α is increasing, E is changing from mostly parallel to more perpendicular to the spheroid. According to the first qualitative principle, this means that E is becoming weaker as α increases; thus, $\underline{E}$ is getting weaker from about $\lambda/d = 1$ to about 0.25, and then it becomes stronger as α decreases again. This factor causes the average SAR to begin to rise rapidly as α decreases. We see, then, that the qualitative principles can be used to explain near-field absorption characteristics as well as plane-wave absorption characteristics.

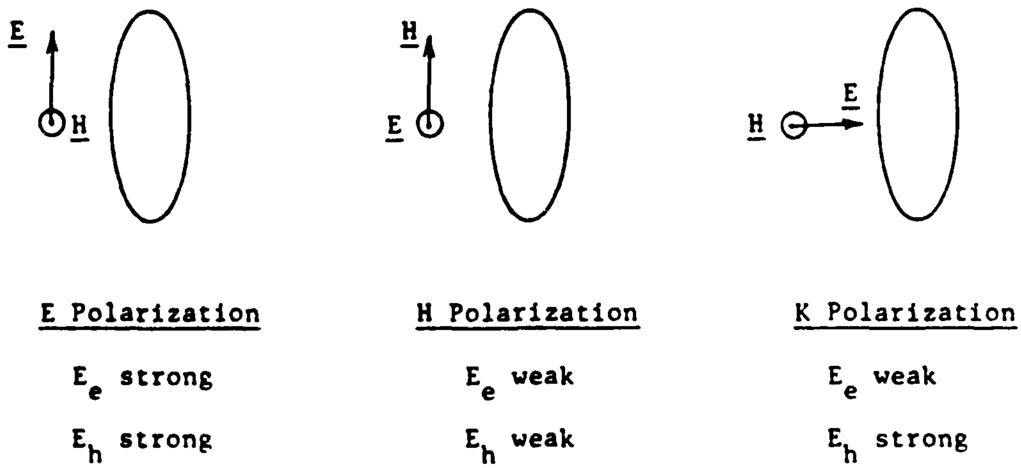

Fig. 11. Qualitative explanation of the differences in average SAR shown in Fig. 2 for the three polarizations in spheroidal models.
$\odot$ means the vector is normal to the paper.

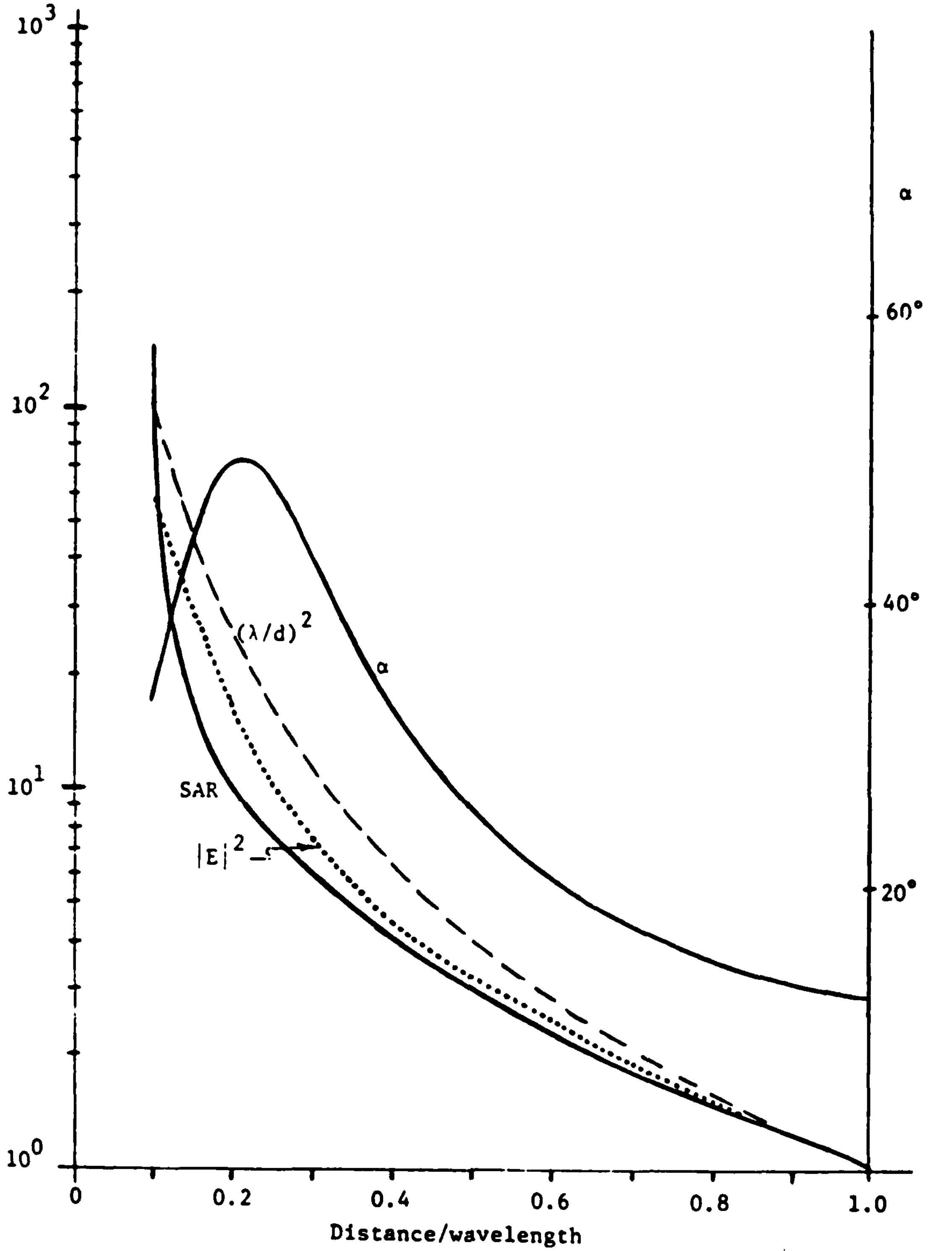

Fig. 12. Calculated values of normalized SAR, normalized $|E|^2$, and angle between $\underline{E}$ and the spheroid's major axis for a spheroidal model of an average man irradiated by a short electric dipole for E polarization at 200 MHz.
d is the distance between the dipole and spheroid
λ is the wavelength of the radiation
α is the angle between $\underline{E}$ and the spheroid's major axis

Adjustments for Frequency Differences

The dosimetric data shown in Fig. 5 allow researchers to extrapolate observed effects in animals to those expected in man. For example, the curve shows that if a rat and a man were both irradiated by a 650-MHz plane wave, the average SAR in the rat would be more than an order of magnitude greater than that in the man. Hence, if a biological effect were observed in a rat with a given incident power density, a similar biological effect would be expected to occur in man at a much higher incident power density. Another important difference would be that the local SAR in the rat would be quite different from that in the man. The heating would tend to be more superficial in the man than in the rat, since compared to a wavelength the size of the man is much larger than the size of the rat.

An approximate numerical extrapolation of experimental results with animals to those expected in man can be made on the basis of the kind of dosimetric information given in Fig. 5. For example, suppose that a biological effect, such as a behavior change, was observed in medium rats irradiated by EM plane waves of 5-mW/cm^2 incident power density at a frequency of 650 MHz, which is approximately the resonant frequency. For the local SARs to be similar in the rat and the man, the wavelength-to-bodylength ratios should be approximately equal in each case. That is,

$$\frac{\lambda_r}{\ell_r} = \frac{\lambda_m}{\ell_m}$$

where λ_r and λ_m are the respective wavelengths for the irradiation of the rat and the man, and ℓ_r and ℓ_m are their respective lengths. For $\ell_r = 0.2$ m, $\ell_m = 1.75$, and $\lambda_r = 0.46$ m (f = 650 MHz), the equation requires that $\lambda_m = 40$ m, which corresponds to a frequency of approximately 75 MHz. This makes sense because Fig. 5 shows that 75 MHz corresponds approximately to resonance in the man. Thus as far as local SAR distribution is concerned, similar patterns would be observed if the rat were irradiated at 650 MHz and the man at 75 MHz.

The incident power density at 75 MHz that would produce the same average SAR in man that occurred in the rat at 650 MHz can also be calculated from the curves in Fig. 5. At 650 MHz, the average SAR in the rat is about 0.8 W/kg for 1 mW/cm^2 and consequently is about 4.0 W/kg for 5 mW/cm^2. At 75 MHz, the average SAR in man is about 0.23 W/kg for 1 mW/cm^2; thus an incident power density of 17.4 mW/cm^2 would be needed to produce 4.0 W/kg in man. So if the change in behavior in the rat were related directly to the average SAR, a similar change in behavior in man might occur upon irradiation at 75 MHz with an incident power density of 17.4 mW/cm^2. A like behavior change in man, however, would probably not be expected to occur if the man were irradiated at 650 MHz with 5 mW/cm^2, because the average SAR would be much lower in the man than in the rat.

These examples show how important the calculated values of the SAR can be in interpreting experimental results. Without the two curves shown in Fig. 5, it would not be clear how observed experimental effects in animals might be related to expected effects in people. Theoretical dosimetry allows comparison at least on the basis of average SAR and approximate local SAR distribution.

SUMMARY

What Can Be Done

Plane Waves--Plane-wave dosimetry, both theoretical and experimental, is a reasonably well-developed discipline. Average SARs can be calculated for models of people and animals over a wide frequency range. The SAR for E polarization can be calculated from a simple empirical formula. Experimental measurements agree fairly well with the calculated results. Average SAR characteristics can be explained qualitatively.

Local SAR distributions can be calculated over a more limited frequency range; and above resonance (70 MHz in man), only at great expense. Local SAR distribution calculations have been verified by experimental measurements only to a limited extent. Usable models of man are not nearly as good for local as for average SAR calculations.

Near Fields--Near-field dosimetry is not as well developed as plane-wave dosimetry. Calculations have been made for SARs produced by simple sources, and calculations are being made for more complicated sources. Some experimental measurements of near-field SARs have been made. Average near-field SARs can be explained qualitatively, but there is no convenient normalization to incident power density for near fields as there is for plane waves. Near-field calculations are much more complicated than plane-wave calculations.

What Needs to be Done

Plane Waves--More work in both theoretical calculation and experimental measurement of local SAR distributions is needed, particularly more verification of the local SAR distributions calculated by numerical methods. More work in calculating temperature distributions produced by RFR should be done.

Near Fields--Theoretical calculations for near-field SARs over a wider frequency range are needed, and for more realistic sources. Methods should be developed for calculating both local and average SARs produced by measured near fields. We need to be able to measure the incident fields at some specific points and then calculate the expected SARs produced in people exposed to those fields. In addition, methods for calculating temperature distributions are needed.

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intense microwave fields. We have further demonstrated that no vasodilation occurs during exposure of the squirrel monkey to infrared radiation of equivalent intensity to the microwaves. This important finding indicates that noncutaneous thermosensitive structures may mediate microwave activation of thermoregulatory responses in the peripheral vasomotor system.

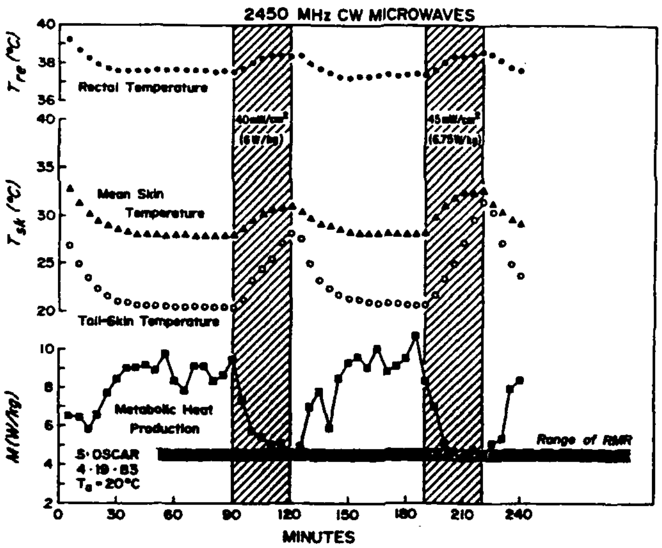


Figure 8. Metabolic heat production and body temperatures of 1 monkey equilibrated to an ambient temperature (T_a) of 20 °C and then exposed for two 30-min periods to 2450-MHz CW microwaves at 40 and 45 mW/cm^2 respectively. The range of resting metabolic rate (RMR) was determined in baseline experiments without microwaves at a thermoneutral T_a of 32 °C. (Unpublished data of Candas, Adair, and Adams).

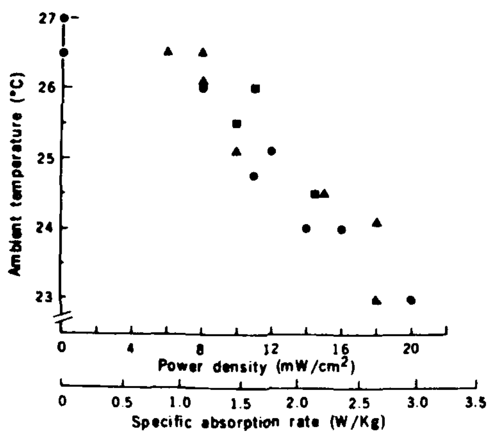


Figure 9. Threshold function for vasodilation of the squirrel monkey tail produced by 5-min whole-body exposures to 2450-MHz CW microwaves. Each data point represents the least microwave power density or absorbed microwave energy required to induce criterion tail-skin warming in three monkeys at the ambient temperature indicated. From Adair and Adams, Science 207:1381-1383 (1980).

In other experiments, when the microwave field was kept on for 90 min, the initial vigorous reduction of metabolic rate, which occurred at the onset of microwave exposure, slowly adapted to the rate of deposited energy, so that when a steady-state was reached, the reduction in metabolic heat production (W/kg) just balanced the rate at which RF energy was absorbed (W/kg). It seems safe to predict that in cool environments, human beings would respond in similar fashion to the presence of low-intensity RF fields. Indeed, this prediction has been quantified by Berglund (1983) and forms the basis of Pound's (1980) proposal to employ 10-GHz microwaves as a source of comfort heating for man.

While the reductions in metabolic heat production shown in Figure 7 were very dramatic, the power densities used in this experiment (2.5 to 10 mW/cm^2) were not sufficient to reduce metabolism to the resting level that obtains within the TNZ (Figure 5). Recent experiments by Candas in my laboratory have explored the consequences of microwave exposures at significantly higher power densities (up to 45 mW/cm^2) on the metabolic response of squirrel monkeys. Results of these studies confirmed that each microwave exposure induces a rapid decrease in metabolic heat production. In a 20 °C environment, for a 10-min exposure the power density required to lower heat production close to the resting level was 35 mW/cm^2. At this intensity the rate of energy absorption, 5.3 W/kg, was comparable to the resting metabolic rate of the animal. Figure 8 shows a representative experiment that featured two 30-min microwave exposures at even higher power densities, 40 and 45 mW/cm^2. During these long exposures, considerable time was required to reduce heat production to the resting level which was then maintained, following cessation of the field, for periods that depended on the power density of the preceding exposure. At the highest power densities explored, vasodilation of the tail vessels occurred, illustrated in Figure 8 by a sharp rise in tail-skin temperature. The vasodilation prevented a dramatic increase in heat storage, evidenced by a minimal increase in rectal temperature. Although vasoconstriction was reinstated subsequent to termination of the microwave field, these data demonstrate convincingly the equivalence between ambient temperature and RF radiation as they selectively influence thermoregulatory responses. Since tail vasodilation normally occurs near an ambient temperature of 26 °C, we may say that in this case a power density of 40 mW/cm^2 (SAR=6.0 W/kg) was the thermoregulatory equivalent of an ~6 °C rise in ambient temperature.

Peripheral Vasomotor Responses. Far less microwave energy is required to initiate tail vasodilation when the monkey is equilibrated to an ambient temperature close to the LCT. As shown in Figure 9, at an ambient temperature (26 °C) just below that at which the vessels of the tail normally vasodilate, criterion dilation was initiated by 5-min exposures at a microwave power density of 8 mW/cm^2. This intensity deposits energy at a rate equivalent to ~20% of the monkey's resting metabolic heat production but produced no observable change in deep-body temperature. In the experiments of Figure 9 (Adair and Adams, 1980), for each 1 °C reduction in ambient temperature below 26 °C, a power density increment of ~4 mW/cm^2 produced identical threshold responses. That Candas' data (Figure 8) do not fall exactly on an extrapolation of the function in Figure 9 indicates different response criteria in the two studies as well as significant procedural differences. Recent data of Gordon (1983c) have confirmed for the mouse that tail vasodilation is proportional to the heat load imposed by exposure of the animal to moderately

i.e., nonpulsed) microwaves at a frequency of 2450 MHz were presented for durations that ranged from 5 to 90 min in individual experiments.

Metabolic Heat Production. Figure 7 shows an experiment that typifies the general protocol employed and demonstrates how 10-min microwave exposures can alter metabolic heat production in a cool (20 °C environment (Adair and Adams, 1982). During the initial 90-min equilibration period, vasoconstriction of the extremities occurred (evidenced by a fall in tail-skin temperature), deep-body temperature stabilized at the normal 39 °C, and metabolic heat production averaged 11-12 W/kg (somewhat higher than in Figure 5 because the air was moving). Subsequent 10-min microwave exposures at a power density of 4 mW/cm^2 and above altered metabolic heat production. At the lower power densities, this took the form of a reduced variability; at 6 mW/cm^2 and above, heat production was significantly lowered below the stabilized baseline level. Figure 7 also indicates that the magnitude of the metabolic reduction was directly related to the intensity of the microwave field. In addition, termination of the field always provoked an abrupt recovery of heat production, sometimes even resulting in a compensatory overshoot. These dramatic alterations in metabolic rate, both during and after brief microwave exposure, ensured regulation of the internal body temperature at its characteristic level throughout the experiment.

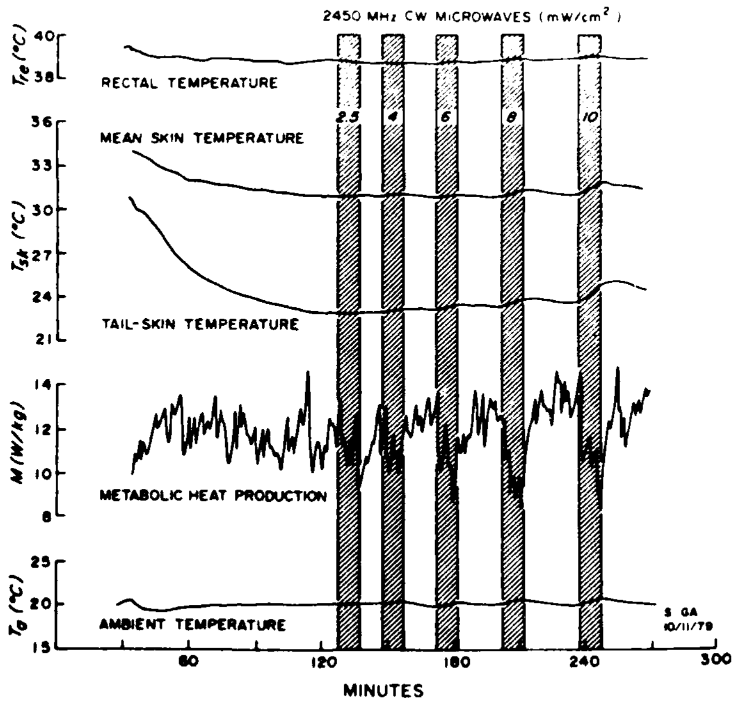


Figure 7. Representative experiment on one monkey equilibrated to an ambient temperature (T_a) of 20 °C to determine how metabolic heat production was affected by 10-min exposures to 2450-MHz CW microwaves of increasing power density. Also shown are rectal temperature (T_{re}) and mean skin and tail-skin (T_{sk}) temperatures. From Adair and Adams, J. Appl. Physiol. 52:1049-1058 (1982).

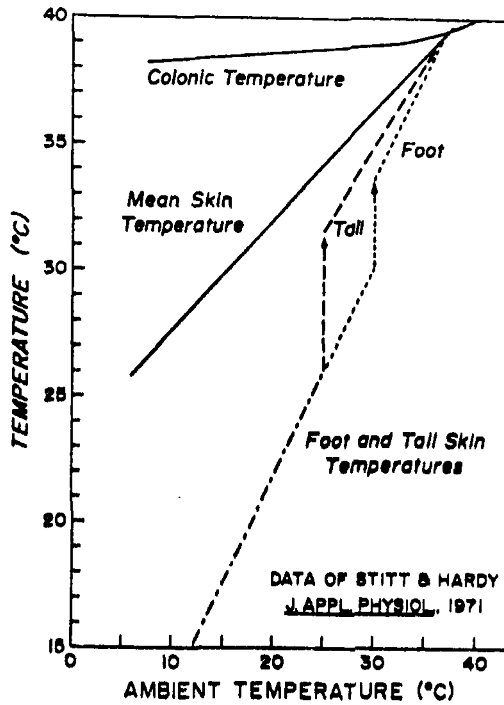


Figure 6. Body temperatures of the restrained squirrel monkey equilibrated to ambient temperatures ranging from 10 to 39 °C. Individual functions show deep colonic temperature, mean skin temperature based on four skin sites, foot and tail-skin temperatures. Arrows indicate vasodilation of vessels in tail and foot skin. From data in Stitt and Hardy, J. Appl. Physiol. 31:48-54 (1971).

Basic Methodology. To test such predictions, individual animals were chair-restrained inside an electromagnetically anechoic chamber at sufficient distance from a horn antenna that the microwave field which irradiated them was very homogeneous. The animal's immediate vicinity was rigorously climate-controlled. A Plexiglas hood over the animal's head collected the expired air which was drawn outside the chamber at 7 L/min for analysis of oxygen content. Metabolic heat production was calculated from oxygen consumption assuming an RQ of 0.83. Deep colonic temperature and the temperatures of four representative skin areas (abdomen, tail, leg, and foot) were read once a minute by an on-line computer. From the four skin temperatures, a weighted mean skin temperature was calculated (Stitt et al., 1971):

$$\bar{T}_{sk} = 0.07\ T_{foot} + 0.37\ T_{leg} + 0.45\ T_{abdomen} + 0.11\ T_{tail}.$$

In some experiments, thermoregulatory sweating from the foot was assessed by changes in dewpoint temperature of air drawn at 1.9 L/min through a Lucite boot enclosing the foot. The animal was always equilibrated to the prevailing ambient temperature before initiation of any microwave exposure. Continuous

hands and feet. An increase in metabolic heat production also occurs in warm environments and is presumably related to increased behavioral activity (attempts to escape the heat). Figure 6 shows an upturn in the colonic temperature function above the UCT, which indicates that the limited capacity for evaporative heat loss through sweating is not sufficient to counteract increased heat production.

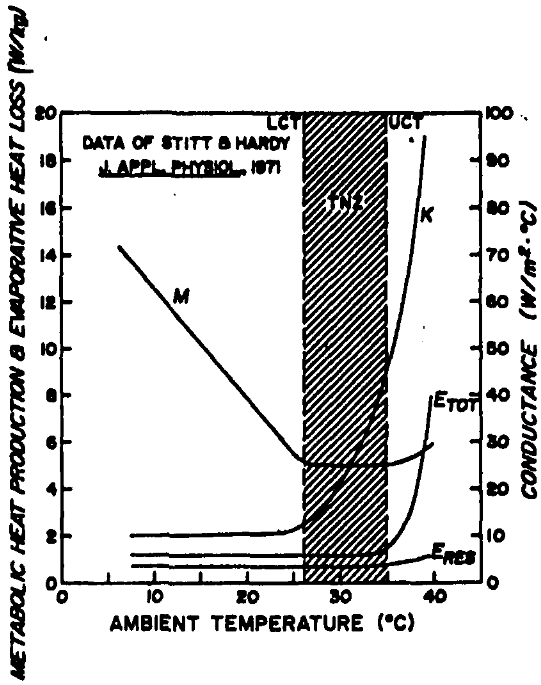


Figure 5. Thermoregulatory profile of restrained squirrel monkey (Saimiri sciureus) across a range of environmental temperatures from 10 to 39 °C. M = metabolic heat production (W/kg); K = conductance ($W/m^2 \cdot °C$); E_{tot} = total evaporative heat loss (W/kg); E_{res} = respiratory evaporative heat loss (W/kg); LCT = lower critical temperature. The region between LCT and UCT is called the thermoneutral zone (TNZ). Data adapted from Stitt and Hardy, J. Appl. Physiol. 31: 48-54 (1971).

THERMOREGULATION IN THE PRESENCE OF RF FIELDS

On the basis of the data presented in Figures 5 and 6, some qualitative predictions can be made about changes in thermoregulatory responses that might be expected if a squirrel monkey were exposed to a radiofrequency field. The particular autonomic effector response that might be altered by absorbed RF energy will be directly related to the ambient temperature at which the exposure occurs. Thus at an ambient temperature below the LCT, microwave exposure should lower metabolic heat production; with the TNZ, microwave exposure should alter peripheral vasomotor tone (conductance); and at ambient temperatures above the UCT, microwave exposure should increase evaporative heat loss, principally via an increase in thermoregulatory sweating.

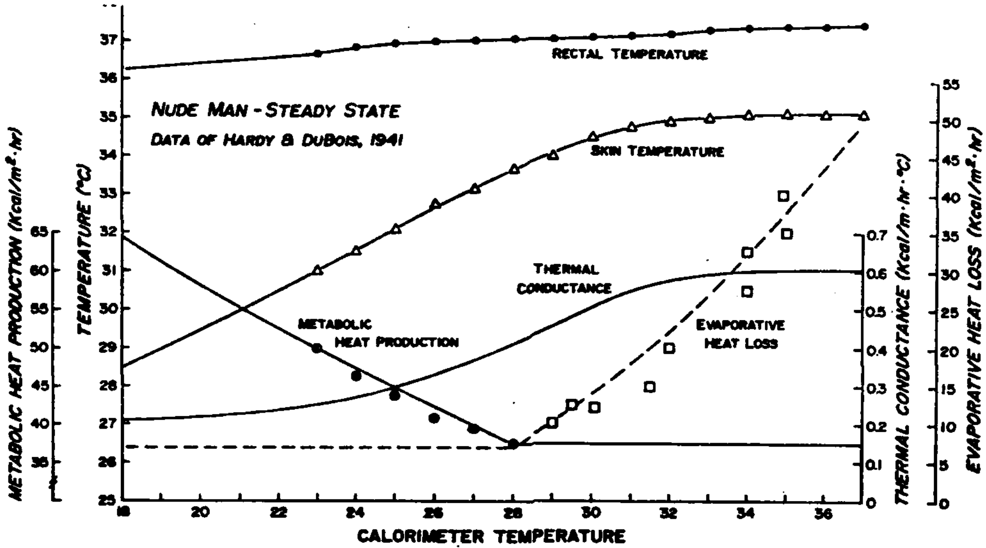


Figure 4. Thermoregulatory profile of nude man equilibrated in a calorimeter to different ambient temperatures. Data adapted from Hardy and DuBois, Proc. Nat. Acad. Sci. 26:389-398 (1941).

Thermoregulation in the squirrel monkey. At the present time it is not prudent to expose human beings to controlled RF fields in controlled thermal environments for the assessment of any responses, thermoregulatory or otherwise. Lacking such a crucial opportunity, it becomes necessary to study, for example, man's close relatives, the nonhuman primates, to derive useful predictive data. Since 1977 the major emphasis of the research in the author's laboratories has concerned the impact of exposure to low-intensity microwave fields on the thermoregulatory capabilities of the squirrel monkey. Our general strategy has been to equilibrate individual restrained animals to certain critical ambient temperatures, determined from the thermoregulatory profile of the species, and then to superimpose controlled exposures to planewave 2450-MHz microwaves at different intensities to determine the microwave threshold for response change. Figure 5 shows the thermoregulatory profile of the squirrel monkey, derived from the partitional calorimetric data of Stitt and Hardy (1971); and the steady-state colonic temperature, weighted mean skin temperature, and the temperatures of tail and foot skin, measured in the same experiments, are shown in Figure 6. Inspection of the figures shows several significant facts. The thermoneutral zone is quite wide, indicating the importance of vasomotor adjustments to thermoregulation in this species. The dramatic discontinuities in the temperature functions for tail and foot skin (Figure 6) reflect vasodilation of the peripheral vessels at different discrete ambient temperatures. As the ambient temperature falls below the LCT (26 °C), metabolic heat production increases linearly at a rate of about 0.35 W/kg·°C. Ambient temperatures above the UCT (35 °C) become increasingly threatening to squirrel monkeys because, although their mode of evaporative heat loss is sweating, sweat is produced only on the friction surfaces of

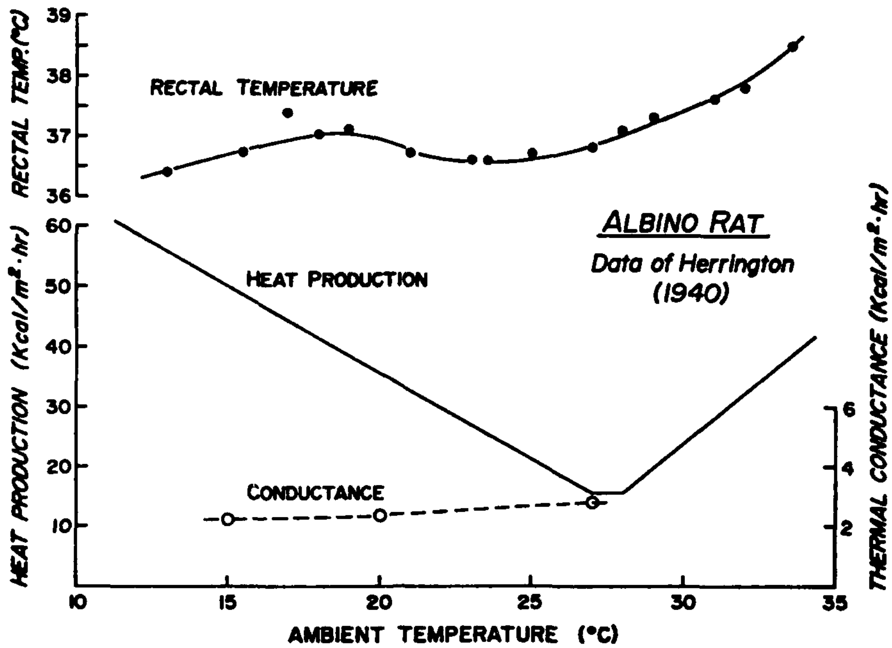


Figure 3. Thermoregulatory profile for the albino rat based on data of Herrington, L.P., Am. J. Physiol. 129:123-139 (1940).

In contrast to the inefficient autonomic thermoregulation of laboratory rodents, man exhibits profound adaptability in the face of environmental thermal stress, particularly in warm environments. Figure 4 shows some of the basic data collected by Hardy and DuBois (1941) for nude men exposed in a calorimeter to a wide range of ambient temperatures. The rectal temperature varies less than 1 °C across a 20 °C range of calorimeter temperature because of the vigorous heat production and heat loss responses. The TNZ is extremely narrow, occurring at about 28 °C in the calorimeter and closer to 30 °C in the natural environment. Above the TNZ, evaporative heat loss in the form of whole-body sweating is initiated that can attain rates of 2-3 liters/h and 10-15 liters/day (Wenger, 1983). Assuming normal rehydration, it is difficult to increase metabolic heat production (by exercise) to levels that cannot be dissipated by sweating. Since human evaporative heat loss is controlled by both internal and peripheral thermal signals (Nadel et al., 1971), only an extraordinarily hostile thermal environment that includes a source of RFR can be expected to pose a serious threat to man's thermoregulatory system. Stolwijk (1983) and others (Way et al., 1981) have recently predicted minimal increases in brain and body temperatures during local absorption of significant amounts of RF energy because of the rapid mobilization of evaporative heat loss and a significant increase in tissue blood flow. Under the assumption that RF exposure provides a thermal stress comparable to exercise (Nielsen and Nielsen, 1965) or an ambient temperature well above the TNZ, such response changes would be predicted from knowledge of human thermoregulatory data such as those depicted in Figure 4.

At ambient temperatures above the LCT, metabolic heat production is at a low, resting level that is characteristic of the species; evaporative heat loss is minimal; and thermoregulation is accomplished by changes in thermal conductance. Conductance is a measure of heat flow from the body core to the skin and reflects the vasomotor tonus of the peripheral vasculature. As the constricted peripheral vessels begin to dilate, warm blood from the body core is brought to the surface so that the heat may be lost to the environment by radiation and convection. These vasomotor adjustments take place within a range of ambient temperatures called the thermoneutral zone (TNZ) that is peculiar to each species. As we shall see, if an endotherm at thermoneutrality is exposed to RFR, augmented vasodilation occurs so that the heat generated in deep tissues may be quickly brought to the skin surface for dissipation to the environment.

The upper limit of the TNZ is known as the upper critical temperature (UCT). At this ambient temperature, the endotherm is fully vasodilated and dry heat loss (by radiation and convection) is maximal. Further increases in ambient temperature provoke the mobilization of heat loss by evaporation either from the skin (sweating) or the respiratory tract (panting). Man and certain other mammals (e.g., many nonhuman primates, horses, cattle, camels) have the ability to sweat copiously to achieve thermoregulation in hot environments. It is reasonable to assume that if these species were exposed to RF radiation at ambient temperatures above the UCT, an increase in sweating rate, in proportion to the strength of the RF field, would result (cf. Adair, 1983). Certain endothermic mammals, notably the rodents, neither sweat nor pant. To achieve some degree of thermoregulation when heat stressed, they must depend upon behavioral maneuvers such as spreading saliva or urine over the pelt.

Figure 3 shows a thermoregulatory profile for the adult albino rat, derived from data of Herrington (1940). It is important to note the very narrow thermoneutral zone, above which metabolic heat production increases significantly. The latter response presumably results from increased activity as the animal attempts to escape from a hostile thermal environment with which it cannot cope autonomically. Some change in thermal conductance can be expected within the TNZ (not assessed by Herrington) as the peripheral veins of the tail vasodilate. However, the rectal temperature function indicates that this popular laboratory subject lacks the innate thermoregulatory capability to withstand extreme environmental temperatures and can rapidly become hyperthermic when heat stressed. Equally vulnerable is the laboratory mouse, which has been the subject of much recent research on the thermoregulatory consequences of exposure to RFR (Ho and Edwards, 1977, 1979; Gordon, 1982 a,b, 1983, a,b; Justesen, 1983). It is essential that the basic thermoregulatory profile of the selected laboratory animal be considered in detail as part of the experimental design of any such research; changes in any measured effector response will depend upon the functional relationship between that response and the ambient temperature.

sensors located in the outermost layers of the skin; other important sites include the medial preoptic/anterior hypothalamic area (believed by many to be the locus of the "central thermostat"), posterior hypothalamus, midbrain, medulla, spinal cord, cortex, and deep abdominal structures. Neural signals from these sensors are integrated by a central controller (perhaps located in the hypothalamus), the integrated signal is compared with the internal reference, and an effector command is generated to energize appropriate responses whenever a load error occurs. A negative load error (i.e., body temperature lower than set point) will produce increased heat production; a positive load error will produce increased heat loss.

The thermoregulatory profile. As noted above, the particular effector response that is mobilized, as well as its vigor, depends upon the prevailing environmental temperature. Figure 2 presents a schematic "thermoregulatory profile" of a typical endotherm, to illustrate how the principal autonomic responses of heat production and heat loss depend on the ambient temperature. The responses are considered to be steady-state rather than transient, and the ambient air is considered to have minimal movement and water content. The figure shows three distinct zones that are defined in terms of the prevailing autonomic adjustment. Below the lower critical temperature (LCT), thermoregulation is accomplished by changes in metabolic heat production, other responses remaining at minimal strength. As the ambient temperature falls further and further below the LCT, heat production increases proportionately. It is clear that RF energy absorbed by an endotherm in a cool environment will spare the metabolic system in proportion to the strength of the RF field (cf. Adair and Adams, 1982); this fact forms the basis of the recent proposal (Pound, 1980) that microwaves be used for the comfort heating of humans in otherwise-cool interior spaces.

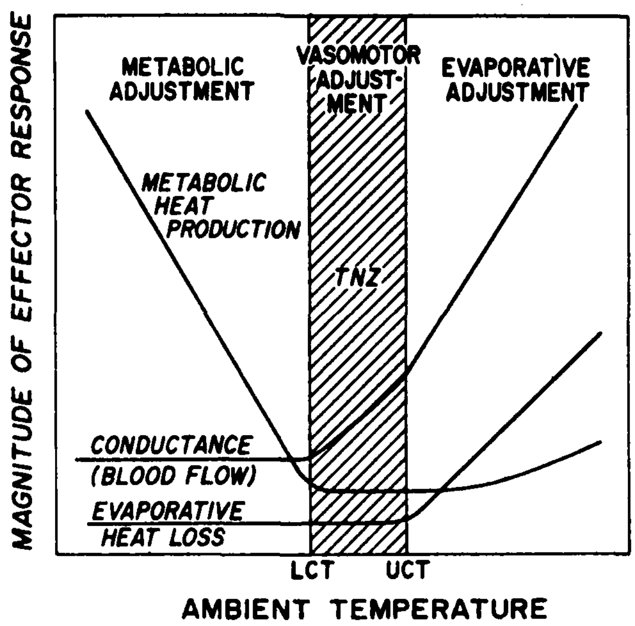
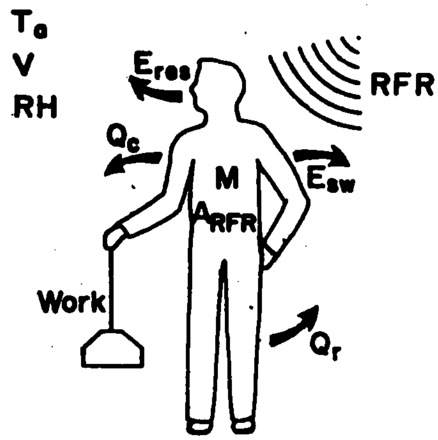


Figure 2. Thermoregulatory profile of a typical endothermic organism to illustrate the dependence of principal types of autonomic responses on environmental temperature. LCT = lower critical temperature; UCT = upper critical temperature; TNZ = thermoneutral zone.

governed by the characteristics of the environment; these include not only the air temperature (T_a) but also air movement (V) and humidity (RH). Two other environmental variables that affect heat transfer (not shown in the figure) are the mean radiant temperature of surrounding surfaces, especially those close to the body, and the amount of body insulation (fur, feathers, fat, clothing).



$$M + A_{RFR} = \text{Work} + E_{res} + E_{sw} + Q_c + Q_r$$

Figure 1. A schematic diagram of the sources of body heat (including radio-frequency radiation, RFR) and the important energy flows between man and the environment. The body is in thermal equilibrium if the equation is balanced. See text for details. Figure modified from Berglund, Microwaves and Thermoregulation (E.R. Adair, ed). New York: Academic, 1984, p. 16.

When the thermal energy produced in the body (including that derived from absorbed RFR) is equal to that exchanged with the environment, the body is said to be in thermal balance; i.e., under these conditions the body temperature remains stable. This can be expressed by the energy (or heat) balance equation shown in Figure 1. When heat production exceeds heat dissipation, thermal energy is stored in the body and the body temperature rises. On the other hand, when more heat is transferred to the environment than can be produced or absorbed, the body temperature falls.

Mobilization of Thermoregulatory Responses. It is pertinent to ask how individual thermoregulatory effector responses (e.g., M or E_{sw}) are mobilized. That is, what is the nature of the control system for the regulation of the body temperature of an endotherm? The thermoregulatory system appears to function like a negative-feedback control system with a reference, or "set" temperature. Temperature sensors are distributed around the body to provide information about local tissue temperatures. Of primary importance are the

INTRODUCTION

Warm-blooded organisms, called endotherms, are capable of maintaining a stable internal body temperature in the face of rather wide fluctuations in the thermal characteristics of the environment. Thermoregulation in endotherms is accomplished by two fundamental response systems, behavioral and autonomic. A wide range of behavioral maneuvers provides a hospitable microclimate for the organism; within this microclimate, fine adjustments in appropriate autonomic responses control the rate at which heat is gained or lost from the body. When the behaviorally generated microclimate is thermally neutral, the involvement of autonomic mechanisms is minimal and the body economizes maximally on stores of energy and water.

The description of thermoregulation in any endotherm involves detailed knowledge of thermoregulatory behavior, both instinctive and learned, as well as knowledge of individual autonomic processes of heat production and heat loss. As we shall see, the particular autonomic response that may be ongoing at any given time is dictated by the prevailing environmental temperature. In other words, endotherms shiver in the cold and sweat or pant in the heat, but not the reverse, and they will avoid doing either if an efficient behavioral maneuver is available to them.

FUNDAMENTALS OF THERMAL PHYSIOLOGY

Heat Exchange Between Organism and Environment. Radiofrequency radiation (RFR) may be regarded conveniently as part of the thermal environment to which man and other endotherms may be exposed. Figure 1 is a schematic representation of the sources of heat in the human body and of the avenues by which thermal energy may be exchanged between the body and the environment. Heat is produced in the body through metabolic processes (M) and may also be passively generated in body tissues through the absorption of radiofrequency radiation (A_{rfr}). In order for the body to remain at a stable temperature, this thermal energy must be continually transferred to the environment. As stated above, the balance between the production and the loss of thermal energy is so regulated by behavioral and autonomic responses that minimal variation occurs in the temperature of skin and body core.

As shown in Figure 1, energy may be lost through the evaporation of water from the respiratory tract (E_{res}) or from the skin (E_{sw}), by dry heat transfer from the skin surface via radiation (Q_r) or convection (Q_c), and by doing work (force x distance) on the environment. (Heat transfer by conduction is usually insignificant in most species and so is not illustrated in this figure.) When the environment is thermally neutral, dry heat loss predominates in the form of convective transfer to the air and radiant transfer to the surrounding surfaces. There is also a small amount of heat lost by the diffusion of water through the skin (not illustrated in the figure). When the temperature of the environment rises above thermoneutrality or during vigorous exercise or defervesence, the evaporation of sweat from the skin surface (E_{sw}) is brought into play to dissipate large amounts of body heat. The rate of heat loss is

THERMAL PHYSIOLOGY OF RFR INTERACTIONS IN ANIMALS AND HUMANS

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Thermoregulatory Sweating. In ambient temperatures that encroach upon the UCT, the body is fully vasodilated, dry heat losses are maximal, and the initiation of evaporative cooling is essential to prevent heat storage and hyperthermia (Figures 2 and 5). Experiments in our laboratory have shown that thermoregulatory sweating from the foot of squirrel monkeys at such ambient temperatures can be reliably initiated by microwave exposure at a power density of 6-8 mW/cm². Figure 10 gives an example of such an experimental session conducted on one monkey equilibrated to an ambient temperature of 34 °C. During the equilibration period, full peripheral vasodilation occurred and internal body temperature was regulated by a reduction of heat production to the resting level. No significant sweating from the foot was evident until the monkey underwent several 10-min microwave exposures of increasing power density to determine the threshold level for the initiation of sweating. The figure shows a reliable, regulated rise in the dewpoint temperature of foot capsule air at 6 mW/cm² and above. This response served to prevent a significant rise in internal body temperature. Many similar experiments on four animals showed that the threshold power density required to initiate thermoregulatory sweating was directly related to the ambient temperature to which the monkey was equilibrated.

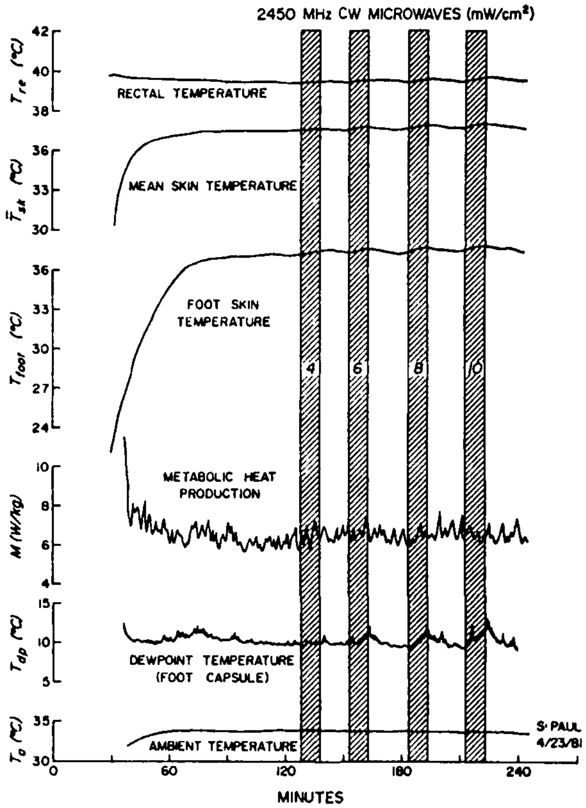

Figure 10. Representative experiment on one monkey equilibrated to an ambient temperature (T_a) of 34 °C to determine effects on metabolic heat production (M) and on dewpoint temperature (T_{dp}) of foot-capsule air of 10-min exposures to 2450-MHz CW microwaves of increasing power density. Also shown are rectal (T_{re}), weighted mean skin ($\bar{T}_{sk}$), and foot-skin (T_{foot}) temperatures.

The magnitude of the change in sweating rate at a given ambient temperature was found to be a function of the intensity of the microwave field. Clearly evident in Figure 10, this result is quantified for one monkey in Figure 11. Each plotted point represents the change in sweating rate that occurred during a single 10-min microwave exposure, plotted against the power density of that exposure. The points for any given ambient temperature are best described by a straight line, the slope of which varies in regular fashion with ambient temperature. Thus at any given ambient temperature at or below 35.5 °C, the higher the power density, the greater the increase in sweating rate; but this increase becomes less and less in cooler environments, i.e., as the skin temperature falls. The relationships displayed in Figure 11 are qualitatively similar to human data reported by Nadel, Bullard, and Stolwijk (1971). The local sweat rate of exercising humans increases linearly as body core temperature rises during exercise in a given ambient temperature. But a higher core temperature is necessary to initiate sweating as skin temperature falls, and the rate of increase in sweating during exercise is lower and lower in cooler and cooler environments. This suggests that in the squirrel monkey the rate of thermoregulatory sweating initiated by microwave exposure depends not only upon the ambient (skin) temperature, but also upon the body-core temperature as it is directly increased by absorbed microwave energy.

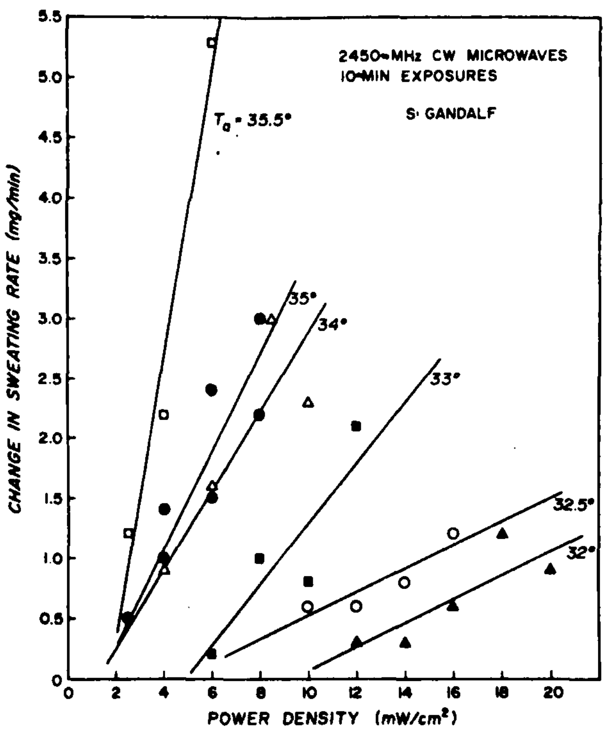

Figure 11. Change in foot-sweating rate from baseline level produced by 10-min microwave exposures at different power densities. The parameter is the ambient temperature (T_a) at which the experiment was conducted. Data from one squirrel monkey.

Much higher thresholds for initiation of evaporative heat loss in the microwave-exposed mouse have been reported recently by Gordon (1982a). In

these studies, the mouse was irradiated inside an opaque waveguide and the increase in relative humidity of air flowing through the waveguide was taken as the measure of heat lost by evaporation of body water. Several difficulties accrue from this preparation. The mouse neither pants nor sweats but is said to increase respiratory frequency somewhat when heat stressed (Gordon, 1983a) *in addition to spreading saliva over the fur; neither of these* responses could be observed. Further, no body temperatures could be recorded to provide evidence that the animals were indeed thermoregulating normally. Finally the ambient temperature during the experiments was 22 °C, well below the TNZ for the mouse and one at which changes in metabolic heat production, not evaporative heat loss, would be anticipated (cf. Figure 3). It is not surprising, therefore, that the heat loss "thresholds" measured in this study were excessively high.

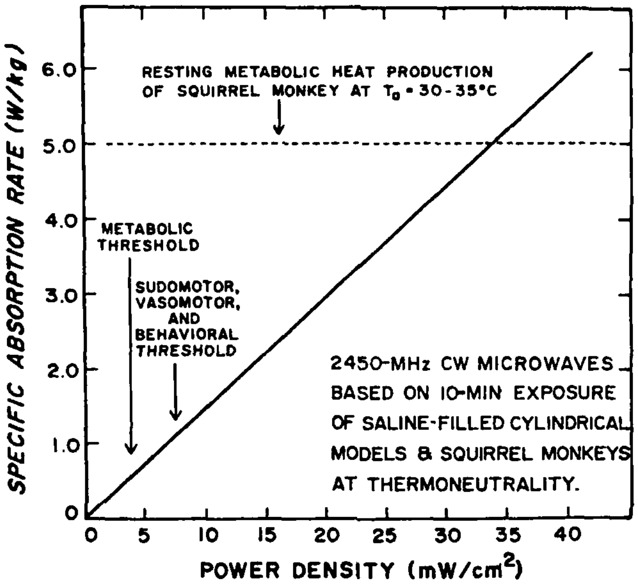

Figure 12. Specific absorption rate (W/kg) as a function of power density calculated on the basis of rectal temperature increments in squirrel monkeys in a thermoneutral environment (35 °C) and on mean temperature increments produced in a 1.1-liter saline-filled cylindrical model by 10-min exposures to 2450-MHz CW microwaves. Model was also equilibrated to an ambient temperature (T_a) of 35 °C. Dashed line at 5 W/kg indicates average resting metabolic heat production of squirrel monkey in TNZ. Arrows indicate microwave thresholds for alteration of thermoregulatory behavior, initiation of tail vasodilation, reduction of metabolic heat production in the cold, and initiation of thermoregulatory sweating in warm environments.

SUMMARY AND CONCLUSIONS

In our own studies we have been impressed by the similarity between the thresholds we have measured for individual responses of heat production and heat loss. Figure 12 summarizes experimentally determined microwave thresholds (5-10-min exposures) for the alteration of four types of thermoregulatory responses in terms of both power density (mW/cm^2) and specific absorption

rate (W/kg). A power density of 6-8 mW/cm^2 will initiate criterion vasodilation of the tail veins in monkeys restrained in a 26 °C environment, an ambient temperature just below the LCT. A slightly lower power density (4-6 mW/cm^2) will reliably lower the metabolic heat production of monkeys equilibrated to 15 and 20 °C environments, while a power density of 6-8 mW/cm^2 will initiate thermoregulatory sweating from the foot of monkeys restrained in a 35 °C environment, an ambient temperature just below the UCT. Although not discussed in this report, we have also demonstrated that the same power density (6-8 mW/cm^2) will reliably stimulate squirrel monkeys to select behaviorally an environmental temperature cooler than that normally preferred.

The remarkable similarity of these thresholds suggests strongly that the same configuration of deep-body thermosensors is being stimulated by absorbed microwaves to provide the neural impetus for response change. The entire thermoregulatory repertoire, autonomic response systems for heat production and heat loss as well as thermoregulatory behavior, that functions over a wide range of ambient temperatures (Figure 5) appears equally sensitive to cope with exogenous deep-body heating. The collective threshold results are reassuring as well: at a rate of RF energy absorption that is equivalent to only 15-20% of the resting heat production of the squirrel monkey, all responses are mobilized rapidly so that little, if any, perturbation of the deep-body temperature occurs. Evidence is also mounting that heat loads derived from RF exposure may be characterized in terms of ambient temperature equivalents. Given man's unparalleled ability to dissipate thermal energy and the encouraging results from thermoregulatory studies on animals such as those described here, it should soon be possible to make reliable predictions of human response changes in the presence of RF fields even though it may be morally indefensible to measure such responses directly.

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CRITICAL REVIEW OF SELECTED TOPICS ON BIOLOGICAL EFFECTS OF RADIOFREQUENCY RADIATION

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INTRODUCTION

Under the sponsorship of the U.S. Air Force School of Aerospace Medicine (USAFSAM), Brooks Air Force Base, Texas, SRI International is analyzing selected articles on the biological effects of electromagnetic radiation. To date, four reports embodying detailed critical reviews of 160 published papers have been issued: USAFSAM-TR-81-24 (November 1981), USAFSAM-TR-82-16 (May 1982), USAFSAM-TR-84-6 (March 1984), and USAFSAM-TR-84-17 (May 1984). The first two reports are available from the National Technical Information Service (NTIS), and the later two from NTIS or USAFSAM.

For convenience, RFR is used as a generic term to include all other designations in the literature for electromagnetic fields at frequencies up to 300 GHz. However, analysis of papers on the effects associated with the high electric and magnetic fields produced by high-voltage power-transmission lines is outside the scope of this paper.

Some of the analyses in those reports served as the basis for a general review of RFR bioeffects, USAFSAM-TR-83-1 (March 1983), which is now undergoing updating; and some of the information presented in this paper was derived therefrom. In the time allotted, however, we will be able to discuss only a few major topics, which were selected as being of most significance with regard to possible hazards of RFR to the public at large. The papers under each topic are discussed in rough chronological order.

SELECTED RFR-BIOEFFECTS TOPICS

EPIDEMIOLOGY

Epidemiology as used here refers to studies of whether one or more health-related conditions can be associated statistically with purported or actual exposure of humans to RFR (in contrast with assessments based on extrapolation from data on animals to humans). Epidemiologic results tend to be based on imprecise estimates of exposure characteristics (frequency, power density, and duration). The extent to which the control group matches the exposed group is sometimes open to question. Because matching of all relevant factors except exposure is the basis for concluding that any observed differences between groups are related to the RFR exposure, selection of an appropriate control group is critical. Despite these limitations, such studies do provide almost the only information available on possible effects of actual RFR exposure in humans.

One of the early concerns was ocular damage from RFR exposure. Various cases of individuals with cataracts ascribed to RFR exposure have been reported from time to time. Indeed, it is likely that in some of these cases, occupational exposure to high levels of RFR had resulted in frank thermal damage to the eye. Not clear, however, was whether chronic exposures to low levels of RFR could be cataractogenic. The following epidemiologic studies of this question are representative.

Zaret et al. (1961) looked for eye defects in a group of 475 persons who were believed to have been exposed to RFR at 11 military and nonmilitary establishments; a group of 359 persons served as controls. The investigators

found a slight but statistically significant difference in defect scores between the two groups, but they expressed some doubt regarding the full validity of the scoring method used.

Cleary et al. (1965) examined Veterans Administration Hospital records of 2,946 Army and Air Force veterans of World War II and the Korean War who had been treated for cataracts. They selected a control sample of 2,164 veterans and, on the basis of military occupational specialties, classified each individual as a radar worker, a nonradar worker, or one whose specialty could not be discerned. In the radar group, they found 19 individuals with cataracts and 2,625 individuals without; in the nonradar group, 21 individuals with cataracts and 1,935 without. (The remaining 510 subjects were in the unspecified occupational category.) These differences between the radar and nonradar groups were not statistically significant.

Cleary and Pasternak (1966) reported on statistical analysis of the records of 736 microwave workers and 559 controls for minor lens changes, using a scoring range from 0 to 3. They reported that the defect scores increased with age for persons in both groups, but that the average score for the microwave group was significantly higher than for the control group. They suggested that this finding is an indication that exposure to RFR may have an aging effect on the lens; however, no cataracts or decreases in visual acuity were found.

Appleton (1973) reported on a study that covered 5 years. Military personnel identified as having been occupationally exposed to RFR from radar and communications systems were matched as closely as possible in age and sex with other military personnel on the same bases who had not been occupationally exposed. Several ophthalmologists independently examined exposed and control personnel (without knowing to which group each individual belonged) for opacities, vacuoles, and posterior subcapsular iridescence, taken as diagnostic precursors of cataracts. Each precursor was scored as either present or absent in each individual, and the binary data were used for statistical analyses by age group and number of persons per age group. The results indicated that more people in older age groups exhibited these precursors, but the pooled data from several installations showed no statistically significant differences between exposed and control groups.

As in other epidemiologic studies, detailed exposure histories (e.g., frequencies, intensities, durations) could not be determined with accuracy, if at all, for either the exposed or the control groups in these ocular studies. The exposed groups, however, likely did receive more RFR exposure. The relatively small research effort devoted to RFR ocular effects indicates that interest has waned in recent years.

Sigler et al. (1965) studied the occurrence of Down's syndrome (mongolism) in U.S. children and found an apparent correlation between this inherited condition and RFR exposure of the fathers of affected children before their conception. However, in a later study by Cohen et al. (1977) in which the original study of 216 children was expanded to 344 children with mongolism, each matched with a normal child of the same sex born at about the same time and whose mother was about the same age, no such correlation was found. Thus the earlier conclusion, based on a smaller sample, that exposure to RFR contributed to mongolism in offspring was not confirmed. No quantitative assessment of the extent of the fathers' exposures was possible.

The incidences of fetal anomalies and death rates reported in birth records for white children born in the vicinity of the Army Aviation Center at Fort Rucker, Alabama, between 1969 and 1972 were evaluated in a report by Peacock et al. (1971) and later by Burdeshaw and Schaffer (1977). Fort Rucker was of interest because of the concentration of radar units on or near the base. Taken together, these reports identified unusually high incidences of certain fetal anomalies and high fetal death rates in the two counties adjacent to Fort Rucker as compared with the corresponding statewide Alabama statistics, and at the Lyster General Hospital (Fort Rucker) as compared with other military and civilian hospitals. (A high incidence of fetal death at the Eglin AFB Hospital was also reported, but no further mention was made of the Eglin data in the remainder of the report.) There was also evidence, however, that the high rates for Fort Rucker could not be attributed specifically to the unquantified radar exposures at or near Fort Rucker on the basis of the birth record data: Coffee and Dale counties ranked only sixth and eighth for anomaly incidence among the 67 Alabama counties: Lyster Hospital's anomaly and fetal death rates were not significantly higher than several other comparable "nonradar" hospitals in Alabama and were in the range of values predicted from carefully controlled studies done in other states. The residences of mothers bearing anomalous infants were not clustered near radar sites, but many of the anomalies reported at Lyster occurred over a small time period, indicating a high anomaly-reporting rate for one or two physicians on the Lyster staff.

Pazderova (1971) published a report on the results of a battery of medical evaluations on 58 employees of Czechoslovakian television-transmitter stations. Exposure frequencies were estimated to range from 48.5 to 230 MHz at field intensities equivalent to 0-0.022 mW/cm^2, with a mean exposure duration of 7.2 years (10.6 h/workday). EKGs, heart and lung X-rays, standard blood tests, urinalyses, and liver-function tests were made, as well as ophthalmologic, neurologic, gynecologic, psychiatric, and psychological examinations. The only statistically significant finding was that the mean plasma protein levels were higher than "normal" values taken from the literature, a finding that the author described as unexplainable. The appropriateness of using literature control values is highly questionable.

In a later study, Pazderova et al. (1974) reexamined the effects of RFR on blood protein levels. The authors indicated that the only difference between exposed and control groups was that the members of the exposed groups had worked irregular shifts, whereas more than half of the control group had worked only morning shifts. The results for both groups showed that the individual levels of blood proteins and their fractions were within normal physiologic limits, but statistically significant differences were found between mean values for the exposed and control groups.

In our opinion, the absences in either study of a control group that had received virtually no RFR exposure renders questionable an interpretation that any differences found were due to RFR exposure. The altered values of blood proteins (which were within normal limits) were likely caused by other factors.

Klimkova-Deutschova (1974) surveyed various industrial worker populations in Czechoslovakia and assessed the health of workers exposed to RFR at 1-150 MHz, 300-800 MHz, or 3-30 GHz, with power densities, where specified, of 0.2

to 3.3 mW/cm^2, depending on their particular occupations. Changes were reported in brain-wave patterns and in blood sugar, proteins, and cholesterol levels, as compared with those in administrative (nonexposed) personnel. Numerical results, however, were not reported and statistical methods were not described.

Siekierzynski (1974) compared the health status and fitness for work of 507 persons in Poland occupationally exposed to pulsed RFR exceeding 0.2 mW/cm^2 average power density (other RFR characteristics not specified) with a group of 334 workers at the same installations exposed to less than 0.2 mW/cm^2. Clinical tests included ophthalmoscopic and neurologic examinations, supplemented by psychological tests and EEGs. No statistically significant differences between the two groups were found. In our opinion the lack of more definite RFR exposure data vitiates, but does not invalidate, the negative findings of this study; i.e., the results provide no evidence for RFR-induced effects on the health status of either group.

Kalyada et al. (1974) reported that their clinical examinations in the USSR of a group of specialists working with RFR generators in the 40- to 200-MHz range for 1 to 9 years showed occurrences of functional changes in the central nervous system, described as vegetative dysfunction accompanied by neurasthenic symptoms. No organic lesions were found, but among the many specific changes reported were deviations in the physiochemical and functional properties of erythrocytes and leukocytes. The authors also conducted experiments with human volunteers and reported functional changes in the thermoregulatory and hemodynamic systems and in the thermal, optical, and auditory "analysers." No RFR intensity values were given, however, for either the specialists or the volunteers; most of the findings were presented in narrative form, with no actual data; and the nature of the control group studied was not described. Consequently, this paper provides little basis for affirming or denying the occurrence of possible adverse effects of occupational exposure to RFR.

Sadchikova (1974) presented clinical observations on the health status of two groups of USSR RFR workers. The 1,000 workers in the first group were exposed to up to a few mW/cm^2, whereas the 180 workers in the second group were exposed to values rarely exceeding several hundredths of a mW/cm^2, both at unspecified "microwave" frequencies. A group of 200 people of comparable backgrounds but presumably not exposed to RFR served as controls. Sixteen kinds of symptoms were reported, including fatigue, irritability, sleepiness, partial loss of memory, lower heart-beat rates, hypertension, hypotension, cardiac pain, and systolic murmur. In the higher power density group, the indices for 5 of the 16 symptoms were higher than those in the lower power density group; they were lower for 9 symptoms and about the same for the remaining 2. Incidences in the control group were lower than those in either exposed group for 15 of the 16 symptoms.

Robinette and Silverman (1977) and Silverman (1979), in an attempt to establish whether exposure to RFR was associated with causes of death or with life expectancies, compiled the mortality records of personnel who had served in the U.S. Navy during the Korean War. By 1977 the records of about 20,000 deceased veterans whose military occupational titles indicated more probable exposure to RFR had been compared with the records of an approximately equal

number of less-exposed veterans. No quantitative exposure data were available. Although no differences between groups emerged in overall mortality rates or in the rates for about 20 specific categories of cause of death, death rates differed significantly for two categories: rates from arteriosclerotic heart disease were lower and those from trauma were higher in the RFR-exposed group. The trauma category included military aircraft accidents; and since a higher proportion of the exposed group had become fliers, attributing the higher trauma death rate to greater previous RFR exposure appeared unreasonable. Overall death rates for both groups were lower than for the general U.S. population of the same age.

The U.S. Embassy in Moscow was subjected to RFR exposure from 1953 until February 1977 (Pollack, 1979). Within rooms having the highest RFR levels (those with windows or doors in outside walls toward the irradiation sources), the average power densities were typically about 0.004 mW/cm^2 within 60 cm of a door or window and 0.0025 mW/cm^2 elsewhere in the room. The highest power density reported was 0.024 mW/cm^2, which occurred in one room during a 2-h period of unusual signal strength on 24 January 1976 (NTIA, 1981). Lilienfeld et al. (1978) compared the health of U.S. personnel assigned to the Moscow embassy from 1953 to 1976 with the health of those assigned to other U.S. Eastern European embassies. The investigators noted several limitations of their study but were able to conclude that no differences were discerned between the Moscow and control groups in total mortality or mortality from specific causes, nor between dependent children or adults of the Moscow and control groups.

Bielski et al. (1980) studied the effects of chronic occupational exposure to RFR in Poland. Two groups were studied: 88 persons in the radio and TV industry exposed 1-20 years to microwaves in the range from 3 to 7 GHz at 0.01-0.2 mW/cm^2 for an estimated 170 h per month, and 68 persons in the furniture industry exposed 1-16 years to HF RFR in the range from 7 to 30 MHz at approximately 0.2-10 mW/cm^2. Groups of 39 and 41 suitably chosen persons were used as unexposed controls for the microwave and HF groups respectively. The results showed that most of the people in the exposed groups complained of nonspecific symptoms--headaches, excessive irritability, increased perspiration, etc.--collectively called "typical symptoms of vegetative neurosis" by the investigators. The frequency of anomalous EEG records and the intensity of EEG changes were reported to be markedly higher among the HF than the microwave workers; however, no statistical tests on the data were reported. Also, it is not clear if the reported differences between exposed and control groups were RFR related or due to other factors. For example, the subjects from the furniture industry were involved with wood-gluing equipment that emitted HF RFR, but the workers were likely also exposed to fumes and vapors from the solvents in the glues.

Lester and Moore (1982a) claimed that U.S. counties with an Air Force base (AFB) operational during 1950-1969 showed statistically significant higher incidences of cancer mortality for that period when compared with counties without an AFB. We reviewed this study in detail and found that the data base used by Lester and Moore was incorrectly assembled. When we reassembled the data base correctly and analyzed it, we found that incidences of cancer mortality in counties with an AFB were not significantly different from incidences in population-matched counties without an AFB, for either males or females.

Lester and Moore (1982b) also reported that a neighborhood pattern of cancer incidence was found in the city of Wichita, Kansas, with the suggestion that it was related to chronic exposure of the general population to microwave radiation from airport radar systems. In their paper they ignored RFR exposure from other sources and used a theoretical model for exposure to airport radars that ignored inverse-square-law attenuation with distance, shielding effects of buildings, etc. The positive correlation of cancer incidence with "exposure" is therefore likely to be spurious. Although the relationship claimed by the authors between radar exposure and cancer incidence may exist, it was not demonstrated by the data and analysis presented in their paper.

In summary, none of these U.S., Polish, and Czechoslovakian epidemiologic studies offers clear evidence of detrimental effects associated with exposure of the general population or of selected occupational groups to RFR. The Soviet findings, which are consistent with the voluminous early Soviet literature, suggest that occupational exposure to RFR at average power densities less than 1 mW/cm^2 does result in various symptoms, particularly those associated with disorders of the central nervous system (CNS). Because the USSR symptomatology has not been reported in western studies and because of the marked differences between Soviet and Western publications in the procedures used for reporting data, it is difficult to accept the USSR epidemiologic studies at face value.

MUTAGENESIS, CARCINOGENESIS, AND CYTOGENETIC EFFECTS

One frequently expressed concern about RFR is that it may be mutagenic or cause cancer. As suggested by Ames (1979), mutagenesis and carcinogenesis are believed to be related, and indeed many chemicals are screened for potential carcinogenicity with bacterial mutation tests.

Several studies for mutagenic effects of RFR at various frequencies, power densities, and durations have been done on bacteria and yeasts by Blackman et al. (1976), Dutta et al. (1979), and Dardalhon et al. (1981). No mutagenic effects attributable to RFR exposure were reported.

Four studies for mutagenic effects of RFR in fruit flies also yielded negative results. In the first study, Pay et al. (1972) exposed male flies to 2.45-GHz RFR at 6,500, 5,900, and 4,600 mW/cm^2 for 45 min. The test consisted of mating the exposed males to females to determine RFR effects on fertility and then remating the offspring to determine the presence of recessive lethal mutations. The results were negative in both cases. In the second study, Mickey et al. (1975) exposed flies to pulsed RFR at 20-35 MHz at an unstated power density for 4 h. The test consisted of observing for nondisjunction of X and Y chromosomes at mating, and the results again were negative. In the third study, Dardalhon et al. (1977) exposed flies to 17- and 73-GHz RFR at 60 to 100 mW/cm^2 for 2 h. No mutations were found. Last, Hamnerius et al. (1979) exposed fly embryos to 2.45-GHz RFR for 6 h at an SAR of 100 W/kg, corresponding to about 200 mW/cm^2. The test system was designed to measure the frequency of somatic mutations for eye pigmentation. As a positive control, flies were exposed to X-rays, a known mutagenic agent. No mutations were found in the specimens exposed to the RFR.

Several studies have been conducted for possible cytogenetic effects of exposure to RFR. Such studies usually involve two types of observations: (1) abnormalities in chromosomes such as fragmentation, fusion, and interchromosomal bridges at the metaphase stage of mitosis; and (2) sister chromatid exchanges.

Chen et al. (1974) exposed Chinese hamster cells and human amnion cells in vitro to 2.45-GHz RFR at power densities ranging from 200 to 500 mW/cm^2 for durations ranging from 1.5 to 20 min. Various chromosome aberrations were observed; but the incidence of aberrations did not increase with increasing power density or exposure duration, and the incidence in exposed cells was not significantly different from that in control cells.

Stodolnik-Baranska (1974) exposed human lymphocyte cultures to 2.95-GHz pulsed RF (pulse characteristics not given) at 20 or 7 mW/cm^2 average power density for periods ranging from 10 min to 4 h. Exposure at 20 mW/cm^2 for 10 min or longer produced chromosome aberrations, but none were reported for exposure at 7 mW/cm^2 for 4 h. The author noted the occurrence of a "slight" temperature increase in cultures exposed at 20 mW/cm^2 but none in cultures exposed at 7 mW/cm^2. The results suggest that if RFR does cause an increase in chromosome abnormalities, the effect may have a power density threshold.

Two studies reported effects of RF on sister chromatid exchange. In the first study, Livingston et al. (1977) exposed Chinese hamster ovary cells in vitro to 2.45-GHz RFR at unstated power density levels and durations. Sister chromatid exchanges were observed in RFR-exposed cells; however, the same level of exchanges was produced in control cells by heating them to the same temperature as that produced by RFR exposure. The authors concluded that the production of sister chromatid exchanges is not related to RFR exposures per se. In the second study, McRee et al. (1981) exposed mice to 2.45-GHz RFR at 20 mW/cm^2, corresponding to an SAR of 21 W/kg, 8 h per day for 28 days. Incidences of sister chromatid exchange in bone marrow cells of exposed mice, sham-exposed control mice, and standard control mice were compared. No statistically significant differences were detected.

A study by Prausnitz and Susskind (1962) implied an association between RFR exposure and cancer incidence. They exposed male mice to pulsed 9.27-GHz RFR at 100 mW/cm^2 average power density for 4.5 min per day, 5 days per week, for 59 weeks. Each day's exposure was equal to one-half of the acute LD-50 of the animals. The major results were (1) progressive testicular atrophy; (2) death of some mice during exposure; (3) a 65% survival rate for the exposed mice at the end of the exposure series as compared with only 50% for the control; (4) the presence of liver abscesses in both groups at necropsy; and (5) leukosis among both groups, with a higher incidence for the exposed mice. Leukosis was described in the paper as "cancer of the white blood cells."

The authors attributed deaths in both groups to a pneumonia infection accidentally introduced into the colony during the experiment, and suggested that the higher survival rate of the exposed mice was due to the protective effect of the "fever" induced by the daily exposures. However, the authors apparently confused leukosis with leukemia or cancer of the circulatory system. Leukosis is defined as an abnormal rise in the number of circulating white blood cells, which can arise from various causes, including stress, endocrine disturbances, and infection such as that causing the liver abscesses found.

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exposures in terms of whole-body SARs and internal SAR distributions in animal carcasses and in physical and mathematical models of various species (including humans). An overview of such work is provided in another paper presented at this NATO Workshop (see Durney, pp. 5-36).

(3) Most experimental data indicating the existence of threshold power densities for various RFR bioeffects were obtained from exposures for relatively short durations. Although it is difficult to conceive of mechanisms whereby long-term RFR exposures at well below threshold values could result in cumulative effects deleterious to health, very few investigations have involved exposure of animals to low-level RFR over a large fraction of their lifetimes. The results of one such study are covered in another paper at this NATO Workshop (see Krupp, pp. 121-133).

(4) Questions of quantitative and/or qualitative differences in bioeffects induced by pulsed versus CW RFR at equivalent average power densities cannot be resolved fully from current knowledge (i.e., some investigators have found no significant differences, whereas others have). Also, it should be noted that although the permissible average power densities in most current and proposed U.S. safety guidelines are applicable to both pulsed and CW RFR, these guidelines do not include maximum allowable pulse power densities per se.

In the light of these uncertainties, the possibility that new information would reveal a significant hazard to humans from chronic exposure to low levels of RFR cannot be dismissed, but seems unlikely.

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Dumanskii and Shandala (1974) and Takashima et al. (1979) used implanted metallic electrodes and reported changes in EEG patterns after acute or chronic exposure of rabbits to RFR. Chou et al. (1982) used implanted electrodes made of carbon instead of metal in an attempt to avoid the field distortion artifact; they reported no significant differences in EEG between rabbits exposed 2 h/day for 3 months at 1.5 mW/cm^2 and control rabbits. Kaplan et al. (1982) used electrodes externally placed after exposure rather than indwelling ones and reported no differences in EEG patterns between control and RFR-exposed squirrel monkeys after more than 12 months of exposure. Rosenstein (1976) exposed rats to RFR from before birth to age 92 days without indwelling electrodes and saw no differences between exposed and control animals when both groups were tested at 140 days of age. Lastly, Chou and Guy (1979) examined EEGs of rabbits with indwelling high-resistance carbon-loaded Teflon electrodes before and during exposure to 2.45-GHz RFR at 100 mW/cm^2. The SAR at the electrodes was about 25 W/kg. No obvious differences were found.

In summary, indwelling metallic electrodes used in studies of the effects of RFR on the EEG or on evoked potentials of the central nervous system may introduce artifactual effects in the preparations under study as well as in the recordings themselves. These artifacts may be minimized by use of electrodes appropriately designed from high-resistivity materials. Experiments in which such specially constructed electrodes were used, or in which electrodes were applied after exposure, showed no evidence of statistically significant differences in EEGs or evoked responses between RFR-exposed and control animals.

UNRESOLVED ISSUES

In this paper, we have critically reviewed selected reports in several RFR-bioeffects topics considered important with regard to possible hazards to humans. Based on the studies examined here and others (USAFSAM-TR-83-1, March 1983) we were not able to cover, we believe that no reliable evidence indicates that chronic exposure to RFR at incident average power densities below 1 mW/cm^2 or at SARs below 0.4 W/kg are hazardous to human health. However, there are several important uncertainties:

(1) Existing epidemiologic studies, though extensive and reasonably well done, are subject to inherent defects such as imprecise classification of the individuals with regard to RFR exposure and unavailability of complete sets of medical reports, death certificates, or health questionnaires.

(2) The most directly applicable experimental evidence relative to possible bioeffects of exposure to the RFR from any specific RFR-emitting system would be from studies in which humans were exposed to the frequencies and waveform characteristics of that kind of system for appropriate durations at the maximum average power densities likely to be encountered. Further quantitative evaluation of many biological endpoints would be necessary. Because such information does not exist, data are obtained from laboratory animals, such as small rodents, used as surrogates for humans--a standard practice for investigating the effects of other agents. Because of the biological differences among species, however, a basic uncertainty is the degree of validity of this practice--which depends in part on the species used, the nature of the agent and its quantitative aspects, and the biological endpoints studied. In investigations of RFR bioeffects, much progress has been made in quantifying

nature of RFR absorption inside the skull of such a small animal at the frequency used could lead to regions in the brain where the SAR would be tens of times higher than that expected from the nominal power density and that rectal temperature measurements in the animals would not reflect such a condition. The observed pathological effects seem likely to have resulted from thermal processes.

Quantitative studies by Albert et al. (1981a) showed that exposure of rats at 10-46 mW/cm^2 prenatally and postnatally decreased the number of Purkinje cells of the cerebellum significantly. A similar study by Albert et al. (1981b) using the squirrel monkey, however, did not show such an effect. Size differences between the heads and brains of the rat and squirrel monkey may have resulted in high local SAR in regions of the rat brain but not in similar regions of the squirrel monkey brain, again indicating that the observed effects seem likely to have resulted from thermal processes.

One study that examined effects of RFR on brain neurochemistry, by Merritt and Frazer (1975), showed no effects on specific neurotransmitters of mouse brain at 19 MHz for 10-min exposures at an E-field of 6 kV/m or an H-field of 41 A/m. Another study, by Sanders et al. (1980), showed a sequence of 5% to 10% changes of biochemical activity in subcellular components associated with tissue respiration at exposure levels of 5 and 13.8 mW/cm^2. The significance of these latter findings is unclear, but they are unlikely to indicate a hazard because of the wide range of tissue respiration values possible under various environmental and activity situations.

In summary, RFR can cause observable histopathological changes in the central nervous system of animals at power densities of about 10 mW/cm^2 or higher, but these changes appear to be thermal in nature. Under special conditions of frequency and skull size, a focusing effect can be obtained in small rodents, causing local SARs tens of times higher than would normally be expected from whole-body SAR measurements. Such conditions do not occur for the adult human skull. One study has reported small changes in brain-tissue respiratory chain function at a power density of 5 mW/cm^2. Such effects are unlikely to be hazardous to humans at power densities of 1 mW/cm^2 or less.

EEG Studies

Studies have been conducted to ascertain the effects of RFR on the EEG or other related electrophysiological properties of the CNS. For EEG measurements made after RFR exposure, the time consumed in placing and attaching the electrodes and the variability of placement introduce problems of interpretation. Additionally, if the effects are transient, they may stop when exposure ceases. For studies attempting to measure EEG changes during RFR, the electrodes and leads used to pick up EEG signals also pick up electrical signals directly from the fields, causing artifacts that render the recordings difficult to interpret. Also, indwelling or chronically attached electrodes will perturb the electric fields in their vicinity and produce great enhancement of energy absorption, as noted by Johnson and Guy (1972) and the National Academy of Sciences (NAS, 1979), thereby creating still another artifact in the biological data. To meet these problems, especially designed indwelling electrodes of high-resistivity materials that do not cause field perturbation have been constructed and used in a few of the more recent studies by Tyazhelov et al. (1977), Chou and Guy (1979), and Chou et al. (1982).

Sutton et al. (1973), Sutton and Carroll (1979), and Lin (1980, 1982) have reported gross permeability increases in the rat BBB when the brain temperature was raised several degrees by RFR heating or the local SAR was several hundred watts per kilogram. Albert et al. (1977, 1979) and Albert and Kerns (1981) found scattered regions of permeability changes in the brains of Chinese hamsters exposed to 2.45-GHz RFR for 2 h at 20 mW/cm^2. Twenty percent of the sham-exposed animals also showed such changes, which were reversible. Presumably, significant heating of local regions of the brain occurred.

Frey et al. (1975) reported alterations in BBB permeability to fluorescein by use of pulsed RFR at average power densities as low as 0.2 mW/cm^2. These findings could not be repeated by Merritt et al. (1978) or Spackman et al. (1978, 1979).

Oscar and Hawkins (1977) reported increased BBB permeability to radiotracer-labeled molecules at average power densities less than 3 mW/cm^2, with pulsed RFR more effective than CW RFR. Merritt et al. (1978), Preston et al. (1979), and Chang et al. (1982) were unable to confirm these findings. Subsequently Oscar et al. (1981) showed with different techniques that their original findings could be explained as due to increases in local cerebral blood flow rather than as increases in BBB permeability.

In summary, RFR can alter BBB permeability at exposure levels sufficient to cause heating of the brain. Exposure at levels of the order of 1 mW/cm^2, considered insufficient to cause heating, have also been reported to alter BBB permeability; but such results have not been confirmed despite several independent attempts to do so. In one case the original findings may have arisen as a consequence of the experimental techniques used.

Histopathology and Histochemistry of the Central Nervous System

Histopathology is defined as the study of diseased or damaged tissues, and histochemistry as the study of the chemical composition of various tissues. Studies of histopathological effects of RFR on the brain have been conducted in both the United States and the USSR. Studies in the USSR have covered a wide range of frequencies, but the dosimetry and methods were inadequately reported for critical review in many instances. Tolgskaya and Gordon (1973) exposed animals (predominantly rats) to RFR between 500 MHz and 1 GHz at 10 mW/cm^2 for 1 h/day for 10 months. They reported detecting various changes from the normal appearance of nerve cells of the brain by unspecified delicate elective neurohistological methods, and that the power density did not raise body temperature. Current knowledge, however, indicates that the method of exposing the animals was such that the SAR must have varied considerably among the animals. The reported changes in appearance were similar to those found by them at 20-240 mW/cm^2 in acute experiments of a frankly thermal nature, and the reported effects in the chronic exposure experiments were probably also of thermal origin.

In the United States, Albert and DeSantis (1975) sought histopathological effects in brains of hamsters exposed to 2.45- GHz RFR at power densities between 10 and 50 mW/cm^2 for periods between 30 min and 24 h and for 22 days. In this study pathological changes were found only in the hypothalamus and subthalamus. Comments after oral presentation of this study noted that the

the tissue and its bathing fluid. They also indicated that the effect was absent for unmodulated RFR but occurred for exposure to 16-Hz modulation alone. For the modulated RFR, the incident average power densities effective in altering the rate of calcium exchange lie between approximately 0.1 and 3.6 mW/cm^2. Within this range, however, not all power densities are effective. There appear to be narrow, effective power-density "windows." Calculations of internal field intensity by Joines and Blackman (1980, 1981) indicate that this factor is important in predicting effectiveness. The mechanisms whereby modulation effects are mediated are speculative.

Of additional interest is a report by Albert et al. (1980) that 16-Hz amplitude-modulated 147-MHz RFR at 2.0 mW/cm^2 increases calcium efflux from pancreatic tissue slices to approximately the same extent as that from neonate chick-brain tissue incubated and exposed under similar conditions. An attempt by Shelton and Merritt (1981) to obtain alterations in calcium efflux from rat brain tissue by use of pulse-modulated 1-GHz RFR was unsuccessful. It is uncertain whether these negative findings were a result of differences in brain tissue, exposure parameters, carrier frequency, or type of modulation.

All of the above studies were carried out on isolated tissues maintained in physiological solutions. Adey et al. (1982), however, have reported that similar alterations in calcium ion exchange occur for exposed brains of paralyzed live cats irradiated at 3 mW/cm^2 with 450-MHz RFR sinusoidally amplitude modulated at 16 Hz.

The effect is scientifically interesting in that it represents a rare instance where RFR may be producing a biological effect by processes other than thermal mechanisms. Interpreting these results with regard to human health and safety is difficult. First, the phenomenon is subtle; large numbers of samples have to be processed to show a statistically significant effect. Second, the observations are highly variable and difficult to reproduce. Third, the circumstances of the experimental methodology are such that the observations of changes of calcium exchange appear to apply to the surface region of the brain rather than to the brain as a whole. Finally, the phenomenon depends on the amplitude modulation of the RFR in a narrow frequency band around 16 Hz and occurs only in narrow power-density windows within 0.1 and 3.6 mW/cm^2.

Blood-Brain-Barrier Effects

In most organs and tissues of the body, molecules in the blood can freely diffuse into the tissue around the capillaries. However, presumably to protect the brain from invasion by various blood-borne microorganisms and toxic substances, large molecules such as proteins or polypeptides exhibit little or no movement from the blood into the surrounding brain tissue in most regions of the brain. The exact manner by which the movement is prevented is still conjectural, but the process is referred to as the blood-brain barrier, or BBB. The BBB can be "opened" by certain agents, such as ionizing radiation, heat, or chemical substances. Studies have been conducted to examine whether RFR also can alter the BBB permeability of animals to various large molecules.

Persons with impaired hearing are unable to hear such clicks, and experimental animals in which the cochlea has been destroyed do not exhibit brainstem-evoked responses.

The original demonstration that acoustic transients can be generated in liquids such as water by transient surface-heating with RFR pulses was provided by White (1963). Foster and Finch (1974) extended this work to show that peak audiofrequency pressures generated in water by specific combinations of RFR pulse power density and pulse width would be sufficient for humans to perceive such pulses as auditory clicks. Lin (1977a, 1977b, 1978, 1980) reported detailed theoretical and experimental studies of the RFR auditory effect. His results indicated that the audiofrequencies produced are not dependent on the RFR carrier frequency but on head size.

Cain and Rissman (1976, 1978) used 3.0-GHz RFR to study the auditory effect in two cats, two chinchillas, one beagle, and eight human volunteers. For the animals, surface or brainstem-implanted electrodes were used to measure the responses to RFR pulses and the responses evoked by audio clicks from a speaker. They found that perception of 10-μs pulses required pulse power densities of at least 1.3 W/cm^2 for both cats, 1 and 2 W/cm^2 for the two chinchillas, and 300 mW/cm^2 for the beagle. The eight humans were given standard audiograms. Because such audiograms do not test hearing above 8 kHz, binaural hearing thresholds were also determined for seven of the subjects for frequencies in the range from 1 to 20 kHz. Five of the subjects could detect 15-μs pulses as clicks; the other three required a pulse duration of 200 μs for perception. No correlation between the results and the audiograms was apparent; however, there was a strong correlation between RFR perception and hearing ability above 8 kHz as determined from the binaural thresholds. The average threshold pulse power density for 15-μs pulses was about 700 mW/cm^2; however, three of the subjects were able to perceive 15-μs pulses at a pulse power density of 300 mW/cm^2, a value taken herein as the nominal threshold for humans.

Olsen and Hammer (1980, 1981) and Olsen and Lin (1981) exposed muscle-equivalent and brain-equivalent models to 5.7- and 1.1-GHz RFR, respectively, at high pulse power densities and detected RFR-induced acoustical responses with hydrophone transducers implanted in the models. Lin and Olsen (1981) also reported that they could detect RFR-induced acoustic pressure waves in the brains of anesthetized cats and guinea pigs by means of a piezoelectric transducer implanted in the cortex.

In conclusion, the preponderance of experimental results indicates that auditory perception of RFR pulses is due to induction of thermoelastic waves in the head rather than to direct brain stimulation by the RFR. Also, because individual pulses can be perceived, it is not meaningful to calculate average power densities for two or more widely spaced pulses and cite such values as evidence that the phenomenon is nonthermal in nature. Almost all of the results are consistent with the thermal expansion theory.

Calcium Efflux

Adey (1979, 1980, 1981a, 1981b) and Blackman et al. (1979, 1980a, 1980b) have reported that exposure of brain-tissue samples from newly hatched chicks to 50-, 147-, or 450-MHz RFR that is amplitude-modulated with frequencies in a narrow band around 16 Hz altered the rate of exchange of calcium ions between

In a study designed primarily for seeking possible effects of chronic RFR exposure on mother-offspring behavioral patterns and the EEG, Kaplan et al. (1982) exposed 33 female squirrel monkeys near the beginning of the second trimester oi pregnancy to 2.45-GHz RFR at whole-body SARs of 0.034, 0.34, or 3.4 W/kg for 3 h per day, 5 days per week, until parturition. The 3.4-W/kg SAR was equivalent to about 10 mW/cm^2. Eight pregnant monkeys were sham exposed for the same periods. After parturition, 18 of the RFR-exposed dams and their offspring were exposed to RFR for an additional 6 months; then the offspring were exposed without the dams for another 6 months.

No differences were found between RFR- and sham-exposed dams in the numbers of live births or in the growth rates of the offspring. The major difference between RFR- and sham-exposed offspring was that 4 of the 5 exposed at 3.4 W/kg both prenatally and after birth unexpectedly died before 6 months of age. These mortality values were too small to place much confidence in statistical inferences. Moreover, these results were not confirmed in a follow-up study of mortality per se reported in Kaplan et al. (1982), in which sufficient numbers of squirrel monkeys were used for adequate statistical treatment.

In summary, in the studies showing demonstrable teratogenic effects of exposure to RFR, power densities or SARs were used that were capable of producing significant heat loads in the animals. In general, the results indicate that a threshold of heat induction or core-temperature increase must be exceeded before teratogenic effects are produced and that RFR per se is not teratogenic.

NERVOUS SYSTEM

Several types of studies have been conducted on effects of RFR on the nervous systems of animals. Such studies have been emphasized in the USSR, where RFR is believed to stimulate the nervous system directly and thereby cause a variety of physiological effects. Many U.S. scientists tend to doubt that RFR interacts directly with the nervous system except, possibly, under special circumstances; they consider most effects of RFR on the nervous system to be indirect results of other physiological interactions.

RFR Hearing Effect

Humans in the vicinity of some types of pulsed radar systems have perceived individual pulses of RFR as audible clicks (without the use of any electronic receptors). This phenomenon has attracted much interest, especially in the United States, because it has often been cited as evidence that nonthermal effects can occur and because one hypothesized mechanism for perception was direct stimulation of the central nervous system by RFR.

Various theoretical and experimental studies with both human volunteers and laboratory animals have been conducted to determine the conditions under which pulsed RFR is audible and to investigate the interaction mechanisms involved. Many of the results support the hypothesis that an RFR pulse having the requisite pulse power density and duration can produce a transient thermal gradient large enough to generate an elastic shock wave at some boundary between regions of dissimilar dielectric properties in the head, and that this shock wave is transmitted to the middle ear where it is perceived as a click.

colonic temperature rise as the RFR. Of 64 rats studied, 7 dams died after RFR exposure, 3 died after IR exposure, and none of the sham-exposed rats died.

On gestation day 19, the 54 surviving dams were euthanized and the numbers of implantations and resorptions were counted. Also, each fetus was examined for morphological abnormalities and its viability and mass were determined. The percentages of living fetuses per dam were about 98% each for the sham and IR groups but only 87% for the RFR group, a statistically significant decrease. The mean fetal mass for the shams was 1.63 g, and the values for the IR and RFR groups were 1.53 and 1.54 g, respectively, both significantly lower than the mean for the shams. No structural abnormalities were evident in any of the 468 formed fetuses, all of which were alive when taken, but severe edema and hemorrhagic signs were endemic in the IR and RFR groups.

The brains of 60 fetuses from sham-, IR-, and RFR-exposed animals were assayed for norepinephrine (NE) and dopamine (DA). The average level of NE for the RFR group was significantly lower than that for the shams but only marginally lower than that for the IR group. The average levels of DA ranked similarly, but the differences were not statistically significant. In their discussion, the authors concluded that "considered in sum, our findings could be taken as evidence that a brief but highly thermalizing application of 2,450-MHz microwaves or of infrared energy have biological effects both comparable and different when averaged colonic temperature changes are equal."

One problem with this investigation was the small number of rats used (a point recognized by the investigators), which necessitated averaging the data in each group over the 10- to 16-day gestation period. This questionable procedure, both biologically and statistically, made it difficult to assess the validity of either the positive or negative results of this investigation.

Berman et al. (1981) exposed 70 rats to 2.45-GHz CW RFR for 100 min daily on gestation days 6 through 15 at 28 mW/cm^2 for an estimated SAR of 4.2 W/kg. The mean colonic temperature at the end of each exposure was 40.3°C. A group of 67 rats was similarly sham exposed. No significant differences between groups were found in pregnancy rates; numbers of live, dead, or total fetuses; incidences of external, visceral, or skeletal anomalies or variations; or body weight of live fetuses.

The investigators surmised "that this lack of an effect may hold true at any exposure level less than that which will kill a significant number of the dams by hyperthermia." They also concluded that the rat is an inappropriate model for determining whether RFR would be teratogenic to humans in exposure situations not lethal for the dams. They then suggested that the mouse fetus is a more appropriate model for assessing such human risk. However, this point is open to question, especially for studies involving chronic low-level exposures. Most of the recent results with mice indicate the existence of a threshold SAR (or power density) for teratogenesis, and the effects above the threshold were evidently due to the heat produced by the RFR. Because the thermoregulatory systems of both the rat and mouse are much less efficient than the human system, neither kind of rodent appears to be a satisfactory model for studying RFR teratogenesis. Any of the nonhuman primates would be more suitable.

weight of the live fetuses in the RFR group was 10% smaller than that of the sham-exposed group, a finding consonant with the investigation's previous results. In addition, ossification of sternal centers was significantly delayed in the RFR mice.

The mice in the other half of each group were permitted to come to term. At 7 days of age, the mean body weight of the suckling mice of the RFR group also was 10% smaller than for the sham group. As before, the survival rate was not affected, but the growth retardation was permanent.

In the first of two regimens, Chernovetz et al. (1975) exposed one group of pregnant mice to 2.45-GHz RFR for 210 min on gestation day 11, and one each of three other groups on days 12, 13, and 14; totaling 20. The estimated mean SAR was 38 W/kg and the total energy absorbed was 5.44 cal/g, which was just sublethal. Four other groups were similarly sham exposed. In addition, eight groups were injected with cortisone, known to be teratogenic. Four of these were similarly exposed to RFR and the other four were sham exposed. All mice were euthanized on day 19, the numbers of implantations and resorptions were counted, and the fetuses were examined for structural abnormalities.

There were no statistically significant differences in the percentage of fetal mortality or structural abnormalities between the RFR and sham groups not administered cortisone, and no dependence on gestation day of treatment. However, the percentage of normal fetuses was 61% for those injected with cortisone and sham exposed, and 50% for the cortisone-with-RFR groups. These percentages were significantly lower than those for the noncortisone group (both 81%), but they did not differ significantly from each other.

In the second regimen used by Chernovetz et al. (1975), the treatments were similar, but the exposures were done only on gestation day 14 and involved a total of 60 dams equally divided among the four treatments. All dams carried to term, and the numbers of pups that survived to weaning at postpartum age 21 days were noted. The noncortisone RFR group produced 93 pups vs 81 for the noncortisone sham group, but the difference was not significant. However, the cortisone RFR group yielded 25 pups and the cortisone sham group only 2. These values were significantly lower than those for the noncortisone groups, and the difference between them was significant. It is tempting to suggest that the higher survival rate of the cortisone RFR group relative to the cortisone sham group indicates that exposure to RFR may afford some protection against teratogenic agents such as cortisone.

In general, these results indicate that absorption of about 5 cal/g of 2.45-GHz RFR is not teratogenic to mice, a finding that is at variance with those of Rugh et al. (1974, 1975) and Berman et al. (1978). Among the possible reasons for these apparently contradictory findings are differences in exposure systems, use of multiple vs individual animal exposures, gross uncertainties in actual doses, mouse-strain difference, variations in dam handling, and differences in gestation day of treatment.

Several similar studies were conducted with pregnant rats. Chernovetz et al. (1977) sham exposed or exposed pregnant rats to 2.45-GHz RFR at a mean SAR of 31 W/kg for 20 min on only one day during gestation days 10 through 17. At this SAR, the colonic temperature increased by 3.5°C. They also exposed rats to infrared radiation (IR) at a temperature that produced the same

study also reported that production of developmental anomalies under worst conditions required exposure for 2 h at a mean SAR of 54 W/kg, which was equivalent to about 192 mW/cm^2.

McRee and Hamrick (1977) exposed arrays of Japanese-quail eggs to 2.45-GHz CW RFR at 5 mW/cm^2, corresponding to an SAR of about 4 W/kg, for 24 h per day during the first 12 days of development. They found no gross deformities in quail killed and examined 24 to 36 h after hatching, and no significant differences in total body weight between RFR- and sham-exposed groups or the weights of the heart, liver, gizzard, adrenals, and pancreas. Blood tests showed statistically significant higher hemoglobin and lower monocyte counts in the RFR-exposed birds, but no differences in the other blood parameters. The differences in mean temperature from egg to egg in the RFR-exposed arrays were as much as 0.5°C, rendering it difficult to associate these positive findings with RFR per se.

In another study, Hamrick et al. (1977) reared the birds from similarly exposed arrays of eggs for 5 weeks after hatching. No significant differences in mortality or mean body weights at 4 and 5 weeks were found between RFR- and sham-exposed groups.

Teratogenic effects of RFR have been reported in several studies with mice and rats. Rugh et al. (1974, 1975) exposed pregnant mice on gestation day 8 to 2.45-GHz RFR at 123 mW/cm^2 for 2 to 5 min, corresponding to doses in the range 3-8 cal/g. On gestation day 18, the litters were examined for resorptions and for dead, stunted, malformed, and apparently normal fetuses. No abnormalities were reported at doses less than 3 cal/g, which corresponded to about 25% to 30% of the lethal dose for these animals. At doses above 3 cal/g, some abnormalities were obtained, notably exencephaly or brain hernia.

Berman et al. (1978) exposed pregnant mice to 2.450-GHz RFR for 100 min daily on gestation days 1 through 17 at 3.4-14.0 mW/cm^2, or on gestation days 6 through 15 at 28 mW/cm^2. Control mice were sham exposed similarly. All mice were euthanized on day 18, and their uteri were examined for the number of resorbed and dead conceptuses and live fetuses. The live fetuses were examined for gross structural alterations and weighed. Ten types of anomalies were tabulated by the numbers of litters affected. Of 318 RFR-exposed litters, irrespective of power density, 27 (8.5%) had one or more live abnormal fetuses versus 12 of 336 (3.6%) of the sham-exposed litters. For most of the specific anomalies, the numbers of litters affected were either too small for statistical treatment or no RFR-related pattern was apparent.

The mean live fetal weights of the litters exposed at power densities of 14 mW/cm^2 or lower were not significantly different from those of the corresponding sham-exposed litters. By contrast, for mice exposed at 28 mW/cm^2 and permitted to come to term, the mean weight of their offspring at 7 days of age was about 10% less than that of control mice. However, there were no differences in survival rate between RFR-exposed and control offspring.

In a subsequent investigation, Berman et al. (1982) exposed a group of pregnant mice to 2.45-GHz RFR at 28 mW/cm^2 for 100 min daily on gestation days 6 through 17. Another group was similarly sham exposed. The mice in half of each group were examined on gestation day 18. The incidence of pregnancy; the numbers of live, dead, and resorbed fetuses; and the total number of fetuses were similar for the exposed and sham-exposed mice. However, the mean body

reliability of the scoring. If the control results from both studies were combined, no mutagenic effect would be evident at any frequency, power density, or duration. Finally, the exposed mice were anesthetized, a condition under which their thermoregulation was impaired, so the temperature increases in the testes may have been much higher than would be predicted from the exposure parameters.

In another study for dominant lethal mutations, Berman et al. (1980) exposed unanesthetized rats to 2.45-GHz RFR at power densities ranging from 5 to 28 mW/cm^2 for 3 h daily, 5 days a week, for up to 3 months. No increases in dominant lethal mutations were evident. Temporary sterility, as indexed by fewer pregnancies, was seen at 28 mW/cm^2 but not at lower power densities. At 28 mW/cm^2, there were significant increases in rectal and intratesticular temperatures.

Two studies searched for possible effects of RFR on mechanisms involved in repair of cellular DNA. Meltz and Walker (1981) examined whether there were any alterations in DNA repair induced by 350-MHz or 1.2-GHz RFR in normal human fibroblasts maintained in vitro after the DNA was damaged by a selected dose of ultraviolet light. Power densities of 1 or 10 mW/cm^2 caused no perturbation of the DNA repair process. Brown et al. (1981) treated mice with streptozocin, a mutagenic/carcinogenic agent known to damage DNA in the rodent liver, and exposed the mice to 400-MHz RFR to determine if excision repair of the DNA would be inhibited. They found that power densities of 1.6 and 16 mW/cm^2, corresponding to SARs of 0.29 and 2.9 W/kg, did not alter the level of excision repair.

In summary, there is no evidence that exposure to RFR induces mutations in bacteria, yeasts, or fruit flies. The results of two studies indicated that RFR induces mutations in mammals; critical review has cast doubt on these findings. Other studies have shown no mutagenic effects of RFR on mammals; evidence for cytogenetic effects is mixed. The lowest power density at which such effects were reported was 20 mW/cm^2, in Stodolnik-Baranska (1974); however, Chen et al. (1974) failed to find cytogenetic effects at 200-500 mW/cm^2. Last, there is no credible evidence that chronic exposure to RFR induces any form of cancer in animals, even at power densities as high as 100 mW/cm^2.

TERATOGENESIS AND DEVELOPMENTAL ABNORMALITIES

Teratogenesis in mammals is the production of physical defects in conceptuses that affect their in-utero development. The term "developmental abnormalities" as used here refers to processes affecting the development of infants after birth. Teratogenic and developmental abnormalities occur naturally at a low rate in most animal species, and relatively little is known about their cause. In a few cases, however, specific agents have been shown to cause significant teratogenic effects; hence, the possibility of teratogenic effects from RFR is an appropriate matter of public concern.

Several studies of RFR teratogenesis in Tenebrio molitor, the darkling beetle, notably those of Carpenter and Livstone (1971), Lindauer et al. (1974), Liu et al. (1975), and Green et al. (1979), indicated that relatively low levels of RFR would produce developmental abnormalities in Tenebrio pupae. In a follow-up study, however, Pickard and Olsen (1979) reported that the number of developmental anomalies depend on such factors as the source of the larvae and the diet fed to them before they entered the pupal stage. This

In addition, two other factors must be considered. First, the incidence of leukosis was greater in the exposed mice, but their survival was also greater. This would be considered unusual for most forms of mouse leukemia. Second, in the exposed mice the incidence of leukosis was greater during but not following exposure. This would imply that spontaneous remission of the "cancer" occurred after cessation of exposure. For true cancer, this would be considered improbable. Overall, the data did not provide any valid evidence that chronic RFR exposure induced any form of cancer in the exposed mice.

In another study involving chronic exposure, Spalding et al. (1971) exposed mice to 800-MHz RFR at 43 mW/cm^2 for 2 h per day, 5 days per week, for 35 weeks. Some deaths occurred during exposure and were attributed to thermal effects caused by faulty positioning of the animal holders. The mean life span of the remaining exposed mice did not differ significantly from that of the controls, general indications of health were the same in the two groups, and the incidence of cancer was the same in the exposed and control mice.

Baum et al. (1976) exposed rats to EMP (electromagnetic pulses) at a rate of 5 per second continuously for 94 weeks. The spectrum of the EMP corresponded to an RFR center frequency of 450 MHz, and each pulse had an intensity of 447 kV/m. The exposures had no effect on blood chemistry, blood count, bone marrow cellularity, fertility, embryo development, cytology, histology, or cancer incidence.

In the first of two studies, Varma and Traboulay (1976) sought to induce dominant lethal mutations by exposing the testes of mice to 1.7 GHz at 50 mW/cm^2 for 30 min or at 10 mW/cm^2 for 80 min. In the second study, Varma et al. (1976) exposed the testes of mice once to 2.45-GHz RFR at 100 mW/cm^2 for 10 min; 3 times in 1 day for 10 min each at 50 mW/cm^2; or 4 times in 2 weeks for 10 min each time at 50 mW/cm^2. In each study, the test consisted of breeding the exposed males to separate groups of unexposed females once each week for 7 to 8 weeks after exposure. Females were killed on the 12th day of gestation, and the uteri were scored for number of implants and number of resorption sites. The authors concluded from the first study that 1.7-GHz RFR was mutagenic under both conditions of exposure, and from the second study that 2.45-GHz RFR was mutagenic for the single 10-min exposure at 100 mW/cm^2 but not for the multiple exposures over time at 50 mW/cm^2.

These studies had a number of flaws. In the first study, errors made in tabulating the data led to uncertainty about the reliability of the numbers presented. In the second study, the fetal late-mortality rates were significantly higher for the exposed mice than for the controls, raising the question of what factors other than RFR might be causing dominant lethal effects. In both studies, systematic errors were made in the computation of the chi-square statistic used to evaluate the significance of the supposed mutagenic effect. If the chi-square is correctly computed, the first study would show a marginal but significant increase in the number of lethal mutations for the study as a whole but not for individual weeks of the study, and the second study would show no increase at all.

In addition, the incidence of dominant lethal mutations in control animals differed significantly for the two studies (1% in the first, 5% in the second), leading to questions about the quality of the animal source and the

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RADIOFREQUENCY RADIATION SAFETY STANDARDS

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SUMMARY

Historically, an average incident power density of 100 mW/cm^2 of microwave radiation was considered hazardous and 10 mW/cm^2 was considered safe. Microwaves were loosely defined as electromagnetic emission at frequencies between 0.3 and 30 GHz. Research conducted over the past few years provides a better scientific basis for radiofrequency radiation (RFR) safety guidelines. RFR is defined to cover the frequency range from 10 kHz to 300 GHz and includes microwaves. Absorption and distribution of RFR are strongly dependent on the size of the irradiated object and the frequency of the incident energy. It has become common practice to report biological effects of RFR as a function of specific absorption rate (SAR) expressed as W/kg. The most widely held view is that the threshold for adverse effects lies above 4 W/kg. This value underlies the rationale for most standards that have emerged since 1982. Using a safety factor of 10, the American National Standards Institute developed RFR protection guides that limit all human whole-body exposures to incident energy that results in an SAR no greater than 0.4 W/kg. This allows incident average power densities from 1 to 100 mW/cm^2, depending on the frequency of the radiation. The American Conference of Governmental Industrial Hygienists applied the same safety factor to establish RF/microwave radiation threshold limit values for occupational workers. The Executive Council of the International Radiation Protection Association also approved interim guidelines to limit human exposures to RFR fields, using a whole-body SAR as the basic limits of exposure. Similar proposals for new RFR safety guidelines have been proposed by the National Radiological Protection Board of the United Kingdom. These new safety guidelines are compared with many other RFR standards used throughout the world today, including NATO STANAG 2345. In general, the new RFR safety standards provide an added margin of safety over those previously used.

INTRODUCTION

The development and application of devices that emit radiofrequency radiation (RFR) have significantly increased the quality of life throughout the world. Yet in recent years the beneficial aspects of radiofrequency/microwave technology have been somewhat overshadowed by a public arousal of the fear of potential adverse effects. This fear, in turn, has led to increased RFR research, resulting in a much better understanding of the interaction of RFR fields and biological systems, and has resulted in the promulgation of new RFR safety guidelines. The new exposure standards are based on what is known about the frequency-dependent nature of RFR energy deposition in biological systems and the current knowledge of biological effects. In general, the new safety guidelines provide an added margin of safety over what was previously used.

RFR is generally identified as nonionizing electromagnetic emission in the frequency range from 10 kHz to 300,000 MHz. Systems and devices that emit such radiation include a vast assortment of radar and communication systems, microwave ovens and other consumer devices, RF heat sealers, radio and television broadcast transmitters, and numerous medical devices for diagnostic and therapeutic purposes.

The inherent risks to health from RFR exposures are directly linked to the absorption and distribution of RFR energy in the body, and the absorption and distribution are strongly dependent on the size and orientation of the body and the frequency and polarization of the incident radiation (1). Both theory and experiment show that RFR absorption in prolate spheroid models approaches a maximum value when the long axis of the body is both parallel to the electric field vector and equal to approximately four-tenths of the wavelength of the incident RFR field (2). Thus, a "standard" 70-kg, 1.75-m human, exposed to a uniform plane-wave RFR field in free space with the E-field aligned with the long axis of the body, would absorb the most energy at a frequency of about 70 MHz (2). If the person were standing in contact with a conducting ground plane (producing a change in the apparent long-axis length), the frequency for maximum RFR absorption would be about 35 MHz. This frequency-dependent behavior is illustrated in Figure 1 for several human sizes (using prolate spheroid models having body masses of 10, 32, and 70 kg). The average whole-body specific absorption rate (SAR) in W/kg is plotted as a function of radiation frequency in MHz for an incident average power density of 1 mW/cm^2.

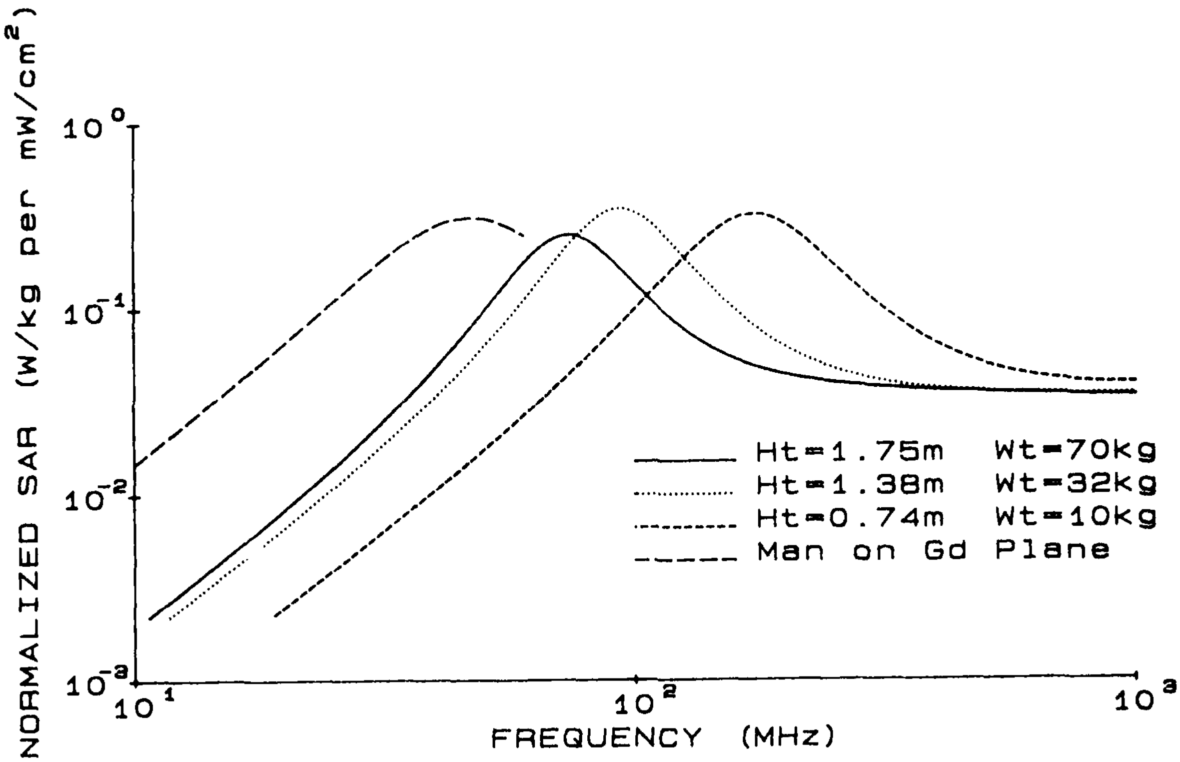

Figure 1. Specific absorption rate for different size humans.

RFR SAFETY STANDARDS

United States RFR Safety Guidelines

American National Standards Institute (ANSI) Standard

For more than 20 years, the United States and most of the free world used a single field-intensity value to maintain the safety of personnel exposed to RFR. A power density of 10 mW/cm^2, time averaged over any 6-minute period, was applied as an acceptable exposure level; and it was generally thought to include a safety factor of 10. During the past 5-10 years, it has become well accepted that the absorption and distribution of RFR in humans are strongly dependent on the frequency of the incident radiation, as shown in Figure 1. Therefore, when ANSI revised its safety standard in 1982, it incorporated this frequency-dependency concept, using SAR as a common denominator for biological effects. The new ANSI standard, published 1 Sep 1982, covers the frequency range from 0.3 MHz to 100 GHz and allows average incident power densities from 1 to 100 mW/cm^2, depending on the radiation frequency. It limits the average whole-body absorption to 0.4 W/kg or less and the spatial peak SAR to 8 W/kg as averaged over any 1 g of tissue (3).

Figure 2 illustrates how the ANSI standard was derived. The relative power absorption curves illustrated in Figure 1 were used to establish the shape of the ANSI curve. It was normalized to 0.4 W/kg because the ANSI committee, after reviewing the biological-effects data base, believed the threshold for adverse biological effects to be greater than 4 W/kg. Thus the 0.4 W/kg was selected to include a safety factor of 10. The ANSI RFR Protection Guides in terms of the mean squared electric (E^2) and magnetic (H^2) field strengths and in terms of the equivalent plane-wave free-space power density as a function of frequency are given in Table 1.

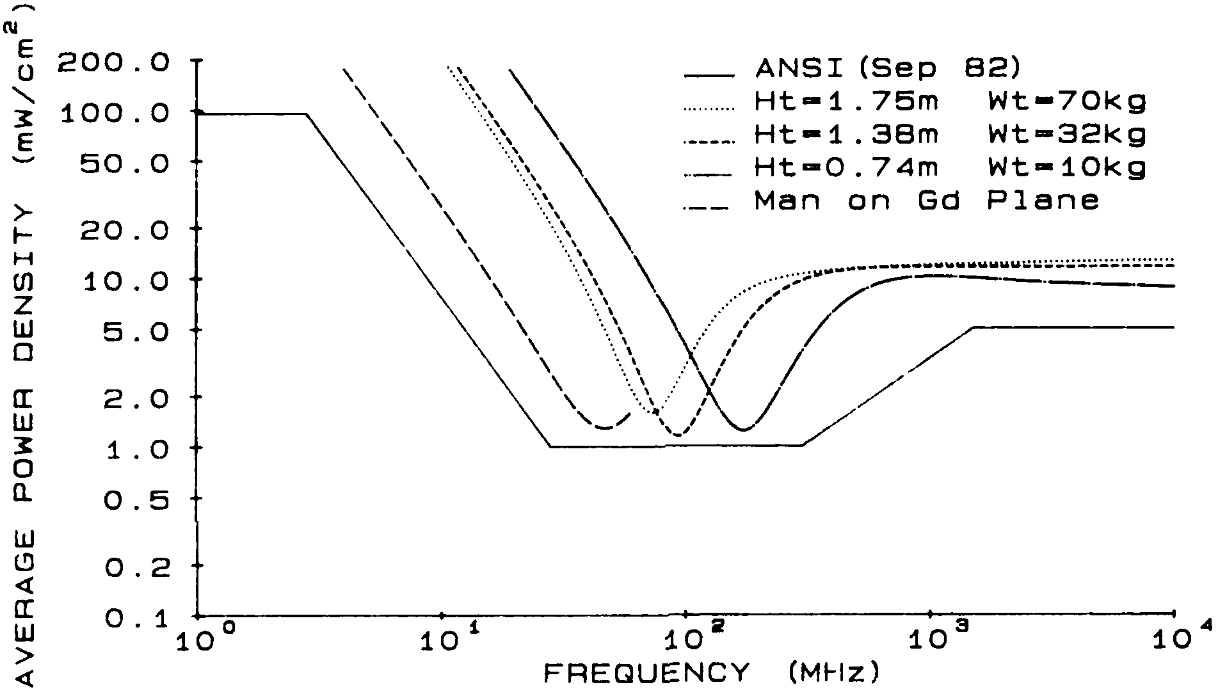

Figure 2. Power densities that limit human whole-body SAR to 0.4 W/kg compared to ANSI standard.

TABLE 1
ANSI Radiofrequency Protection Guides

Frequency Range (MHz)	E^2 (V^2/m^2)	H^2 (A^2/m^2)	Power Density (mW/cm^2)
0.3 - 3	400000	2.5	100
3 - 30	$4000(900/f^2)$	$0.025(900/f^2)$	$900/f^2$
30 - 300	4000	0.025	1.0
300 - 1500	4000(f/300)	0.025(f/300)	f/300
1500 - 100000	20000	0.125	5.0

American Conference of Governmental Industrial Hygienists (ACGIH) TLV

In May 1983, ACGIH published new threshold limit values (TLVs) for radiofrequency/microwave radiation (4). Like the ANSI standards, the ACGIH TLVs limit human absorptions to an SAR of 0.4 W/kg or less, averaged over any 6-minute period. Unlike the ANSI standards, the TLVs cover the added frequency range from 10 to 300 kHz and from 100 to 300 GHz. Because the TLVs are to be applied in occupational settings, they assume that no children (small humans) will be in the workplace. This assumption allows an average incident power density of 10 mW/cm^2 at frequencies greater than 1 GHz, while maintaining the same 0.4-W/kg whole-body absorption limit. This can be seen from Figure 2 if the absorption curve for a 10-kg human is removed. The arbitrary 100-mW/cm^2 cap applied in the frequency range from 10 kHz to 3 MHz appears safe on the basis of whole-body SAR. However, RFR intensities of 100 mW/cm^2 may result in shocks and/or burns under certain conditions if proper insulation techniques are not used. The 100-mW/cm^2 limit should not restrict many operations and serves as a reminder that a person can begin to encounter potentially significant problems at such levels. The ACGIH TLV provides procedures to avoid these problems and to maintain personnel safety while reducing operational constraints. The ACGIH TLVs are established as safety guidelines for the workplace. They are intended for use in the practice of industrial hygiene and should be interpreted and applied only by a person trained in this discipline. The ACGIH TLVs are presented in Table 2.

TABLE 2
ACGIH Radiofrequency/Microwave Threshold Limit Values

Frequency	Power Density (mW/cm^2)	E^2 (V^2/m^2)	H^2 (A^2/m^2)
10 KHz to 3 MHz	100	377,000	2.65
3 MHz to 30 MHz	$900/f^2$	$3770 \times 900/f^2$	$900/37.7\ f^2$
30 MHz to 100 MHz	1	3770	0.027
100 MHz to 1000 MHz	f/100	3770 x f/100	f/37.7 x 100
1 GHz to 300 GHz	10	37,700	0.265

mW/cm^2 = milliwatts per centimeter squared
f = frequency in MHz

Federal Guidelines

The United States has not established federal guidelines for RFR exposures. The voluntary guidelines offered by ANSI and ACGIH coupled with those used by the individual services of the Department of Defense and some State standards (Massachusetts, New Jersey, and Connecticut), represent the RFR safety guidelines applied in the United States in the past few years (5,6).

International Radiation Protection Association

On 8 July 1983, the Executive Council of the International Radiation Protection Association (IRPA) approved interim guidelines on limits of exposure to radiofrequency electromagnetic fields in the frequency range from 100 kHz to 300 GHz (7). The International Nonionizing Radiation Committee of IRPA included participants from France, Netherlands, Poland, Denmark, Germany, Great Britain, Australia, and the United States. Environmental Health Criteria 16, "Radiofrequency and Microwaves," published in 1981, serves as the primary scientific rationale for the development of the IRPA RFR guidelines (8). These guidelines apply to RFR exposure of occupational workers and the general public. The basic limits of exposure for frequencies greater than 10 MHz are expressed in whole-body averaged SAR. For practical purposes, derived limits of exposure expressed in average incident power density are also given. See Tables 3 and 4. The derived limits are extremely conservative in the frequency range 10-30 MHz. This approach, to state the exposure limit in terms of whole-body SAR, represents a departure from current practices; i.e., even though they are based on limiting the whole-body SAR, most new standards express the permissible exposure levels in average incident power density. For occupational workers, the IRPA exposure limit for frequencies greater than 10 MHz is 0.4 W/kg when averaged over any 6 minutes and over the whole body, or 4 W/kg when averaged over any 6 minutes in any 1 g of tissue. For the general public, the IRPA exposure limit is five times lower; i.e., 0.08 W/kg when averaged over any 6 minutes and over the whole body or 0.8 W/kg when averaged over any 6 minutes and any 1 g of tissue.

TABLE 3
IRPA Occupational Exposure Limits to Radiofrequency Electromagnetic Fields

Frequency MHz	E (V/m)	H (A/m)	Power Density (mW/cm^2)
0.1-1	194	0.51	[a]10
>1-10	$194/f^{1/2}$	$0.51/f^{1/2}$	[a]10/f
>10-400	61	0.16	1
>400-2000	$3/f^{1/2}$	$0.008/f^{1/2}$	f/400
>2000-300,000	137	0.36	5

[a]These values are provided for information only and are not to be considered for determining compliance.

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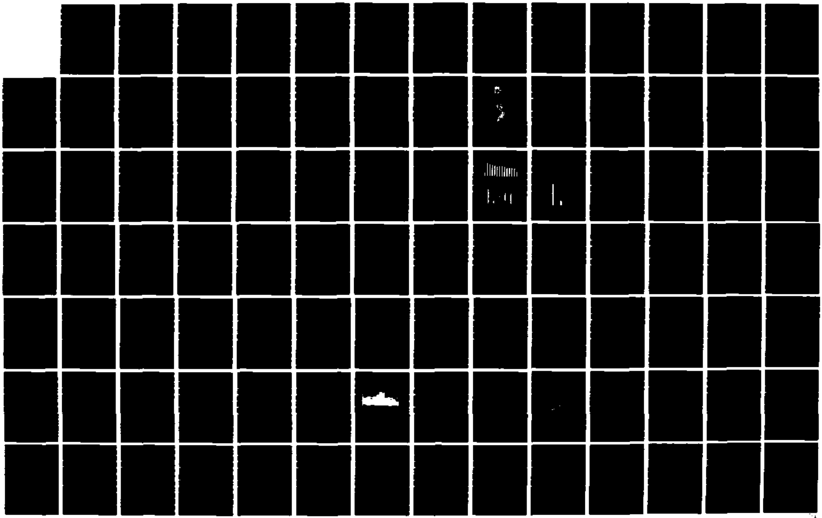

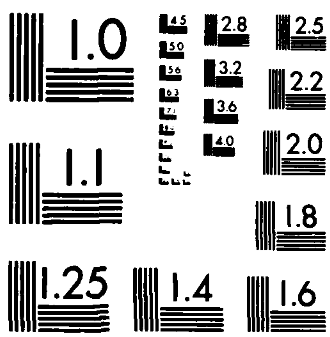

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TABLE 4
IRPA General Public Exposure Limits to Radiofrequency Electromagnetic Fields

Frequency MHz	E (V/m)	H (A/m)	Power Density mW/cm^2
0.1-1	87	0.23	[a]2
>1-10	$87/f^{1/2}$	$0.23/f^{1/2}$	[a]2/f
>10-400	27.5	0.073	0.2
>400-2000	$1.375f^{1/2}$	$0.0037f^{1/2}$	f/2000
>2000-300,000	61	0.16	1

[a]Values are for information only, not for determining compliance.

Figure 3 presents a comparison of the ANSI, ACGIH, and IRPA RFR safety standards plotted as average incident power density versus frequency. These standards are all based on the assumption that 4 W/kg is a reasonable threshold for adverse biological effects. Differences in the permissible incident power densities as a function of frequency result from the degree of conservatism applied in each instance.

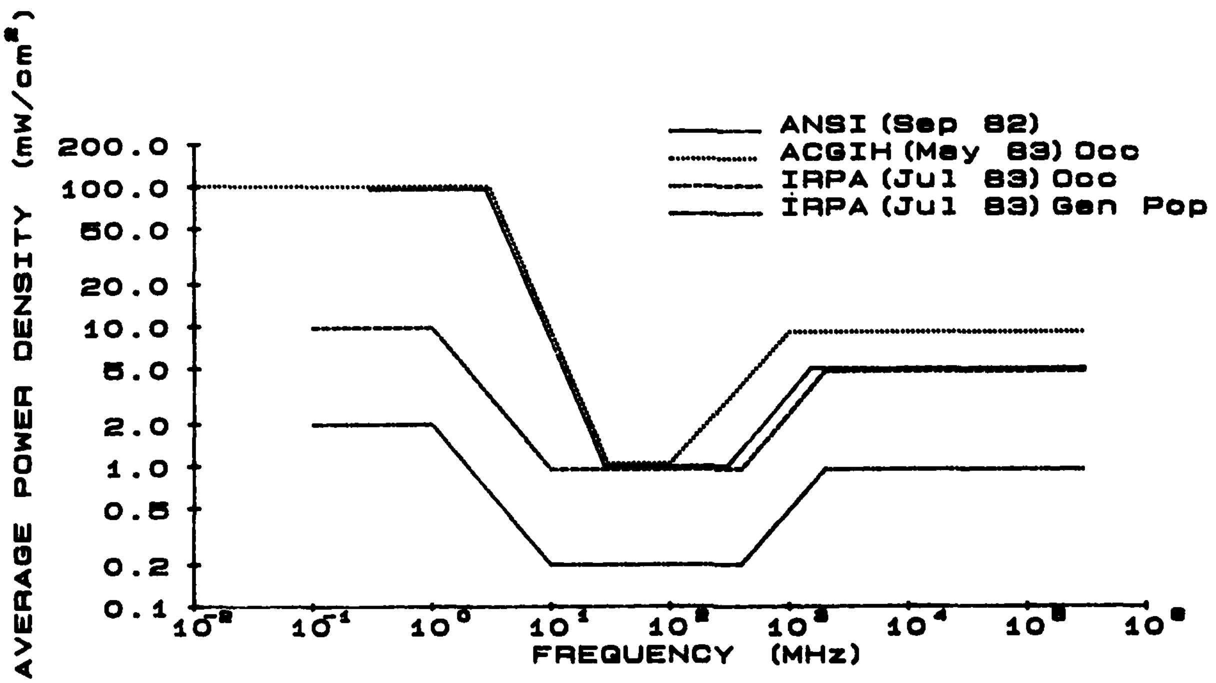

Figure 3. Comparison of RFR safety guidelines based on an adverse-effect threshold of 4 W/kg.

United Kingdom

For many years the United Kingdom (UK) used the 10-mW/cm^2 standard for RFR exposures over the frequency range from 30 MHz to 30 GHz. In 1983 the National Radiological Protection Board of the UK proposed new safety guidelines. The proposed limits for continuous exposure of adult populations are essentially the same as the ACGIH TLV standard previously described. The proposed limits for the general population, including children, are essentially the same as the ANSI standard, except the UK proposal extends the lower frequency limit down to 3 kHz and the upper frequency limit to 300 GHz. These proposals and the rationale used are described in Radiological Protection Bulletin No. 52, dated May 1983 (9).

Canada

The Canadian federal government also used the so called 10-mW standard until 1979; then it revised its standard to include separate occupational and nonoccupational guidelines (10). The maximum permissible exposure level for the general public (nonoccupational) is 1 mW/cm^2 for the frequency range 10 MHz to 300 GHz. For occupational situations, the maximum exposure levels are frequency and time dependent. From 10 MHz to 1 GHz, the Canadian RFR standard permits exposure to 1 mW/cm^2 for an 8-hour work day, 10 mW/cm^2 for 6 minutes or less, and 25 mW/cm^2 for 2.4 minutes or less; from 1 to 300 GHz exposures, 5 mW/cm^2 for an 8-hour work day, 10 mW/cm^2 for 30 minutes, and 25 mW/cm^2 for 2.4 minutes are permitted.

Sweden

In 1976 Sweden published a standard that allows exposures (averaged over any 6 minutes) of 5 mW/cm^2 for the frequency range 10 to 300 MHz for 8 hours and 1 mW/cm^2 for 300 MHz to 300 GHz. It also limits the maximum average power density to 25 mW/cm^2.

USSR

RFR exposure limits in the USSR and other Warsaw Pact countries are generally recognized as being lower than those of Western countries. This results primarily from differences in philosophy and processes for setting standards (11). In the United States, safety factors are usually applied to values at which biologically significant effects are observed in laboratory animal studies. In the USSR, the principle of "no effect," adverse or otherwise, on any person appears to be the primary basis for standard setting. A recent publication of the World Health Organization states, "The USSR occupational and public safety standards are based on the principle of complete prevention of health risks, and, therefore, include large safety factors" (8). Until recently, the maximum level for 24-hour exposure of the general population was 5 μW/cm^2. Recent visitors to the USSR report that this has been changed t^ 10 μW/cm^2. The occupational exposure levels are summarized in Table 5 (9). The Soviet military organizations are exempt from such standards, but it is likely that they use RFR exposure levels 10 times higher for their military guidelines. Other Warsaw Pact countries, such as the German Democratic Republic and Bulgaria, appear to use essentially the same RFR standards as the USSR.

TABLE 5
USSR Maximum Levels for Occupational Exposure to Radiofrequency Radiation

Frequency (GHz)	Exposure Duration	Exposure Limit
0.01 to 0.03	Working Day	20 V/m
0.03 to 0.05	Working Day	10 V/m 0.3 A/m
0.05 to 0.3	Working Day	5 V/m 0.15 A/m
0.3 to 300	Working Day	[a]0.01 mW/cm^2 [b]
	Working Day	0.1 mW/cm^2 [c]
	2 h	0.1 mW/cm^2 [b]
	2 h	1 mW/cm^2 [c]
	20 min	1 mW/cm^2 [b]

[a]Using the recent proposals that the product of average power density and exposure time should not exceed 720 $mW\text{-}s/cm^2$, the exposure limit becomes 0.025 mW/cm^2 instead of 0.01 mW/cm^2.

[b]Stationary antennas.

[c]Rotating antennas.

In March 1983 B.M. Savin reported on proposed changes to the USSR microwave exposure standards (12). The proposals served as the basis for developing Amendment No. 1 to State Standard 12.1.006-76 CCBT, "The Electromagnetic Fields of Radio Frequency--General Requirements." The average power density is still the basic parameter used to assess compromise of state-of-health, but maximum power density is to be determined by the allowable energy load on the body and the exposure duration. The maximum power density will be determined by dividing the energy density by the exposure time. The maximum energy density allowed is equal to 720 $mW\text{-}s/cm^2$ (or in the case of rotating or scanning antennas, 7200 $mW\text{-}s/cm^2$). Also, the maximum permissible average power density shall not exceed 1 mW/cm^2 for 12 minutes.

This new approach by the USSR in establishing permissible microwave exposure levels is in agreement with modern understanding of the dependence of RFR bioeffects on heat load. The proposed changes are apparently based on information developed by the Institute of Occupational Health and Disease of the Professions of the USSR Academy of Medical Sciences.

NATO STANAG 2345

In 1975, Research Study Group 2 on Protection of Personnel Against Non-Ionizing Electromagnetic Radiation (Panel VIII of AC/243 Defence Research Group, NATO) proposed a revision to STANAG 2345. The intent of the proposal

was to revise the STANAG to incorporate frequency-dependent-RFR safety guidelines. These changes are documented in the current NATO Standardization Agreement (STANAG) 2345 (MED), "Control and Recording of Personnel Exposure to Radiofrequency Radiation." The maximum permissible exposure levels averaged over any 6-minute period for continuous wave, modulated, or pulsed radiation are presented in Table 6 (13).

TABLE 6
STANAG 2345--Limitation of Exposure for Personnel

Frequency Range	Average Power Density
10 kHz - 1 MHz	265 mW/cm^2
1 MHz - 10 MHz	66 mW/cm^2
10 MHz - 300 GHz	10 mW/cm^2

Figure 4 compares the NATO STANAG 2345, ANSI, IRPA, and USSR standards. Almost all RFR safety guidelines being used today will fall within the range of those presented in Figure 4.

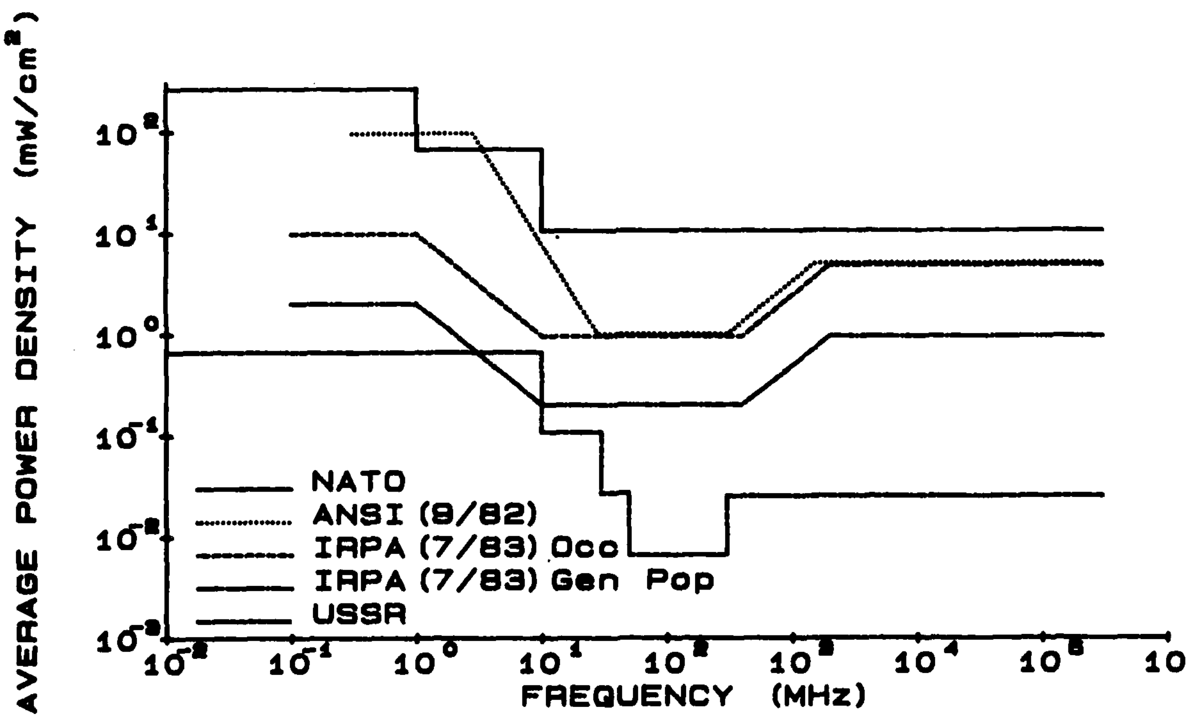

Figure 4. Comparison of RFR safety guidelines.

DISCUSSION

Since most RFR standards include some form of time averaging to limit personnel exposures, comparing them on that basis is appropriate. Figures 5 and 6 present the permissible power density in mW/cm^2 versus exposure time in minutes for two frequency bands for several of the standards discussed above. Tables 7 and 8 present the same comparisons, including the SAR and specific absorption (SA) values. Reviewed in this manner, these data illustrate the fact that for relatively short-term exposures the differences in current RFR standards used throughout the world are not great.

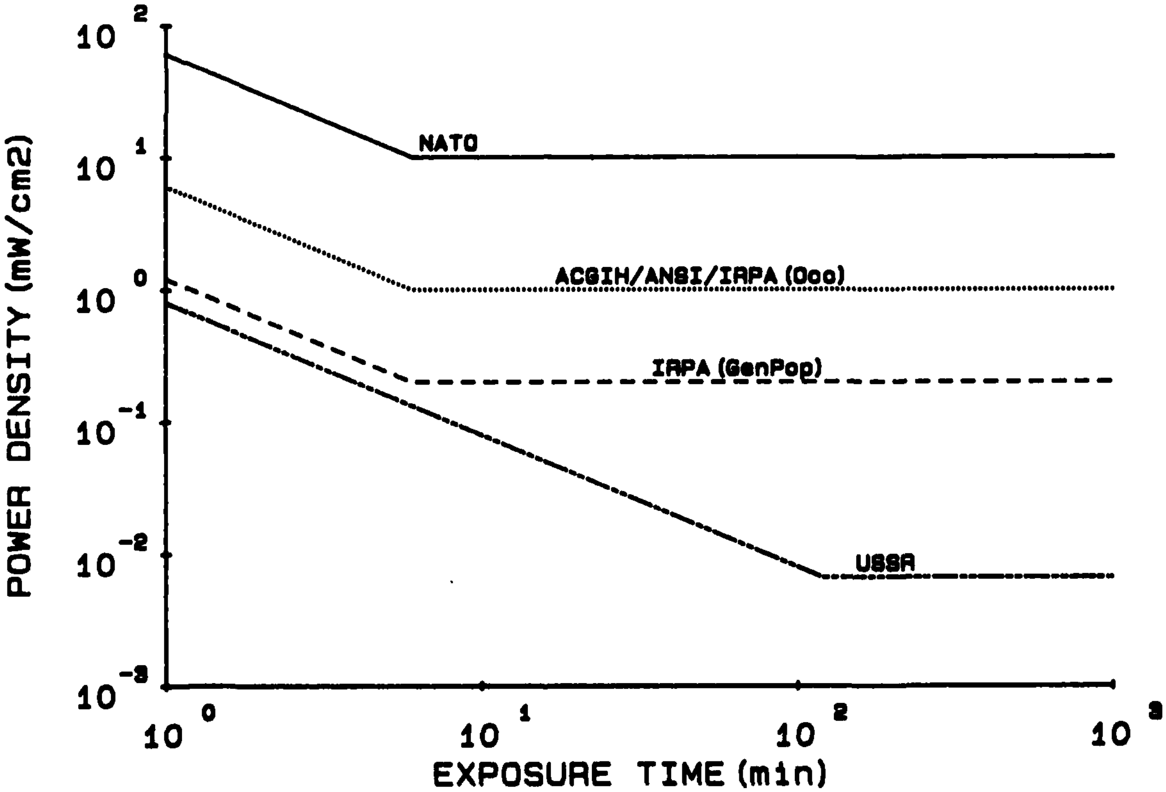

Figure 5. Power density vs exposure time (for frequencies 30 MHz - 2 GHz).

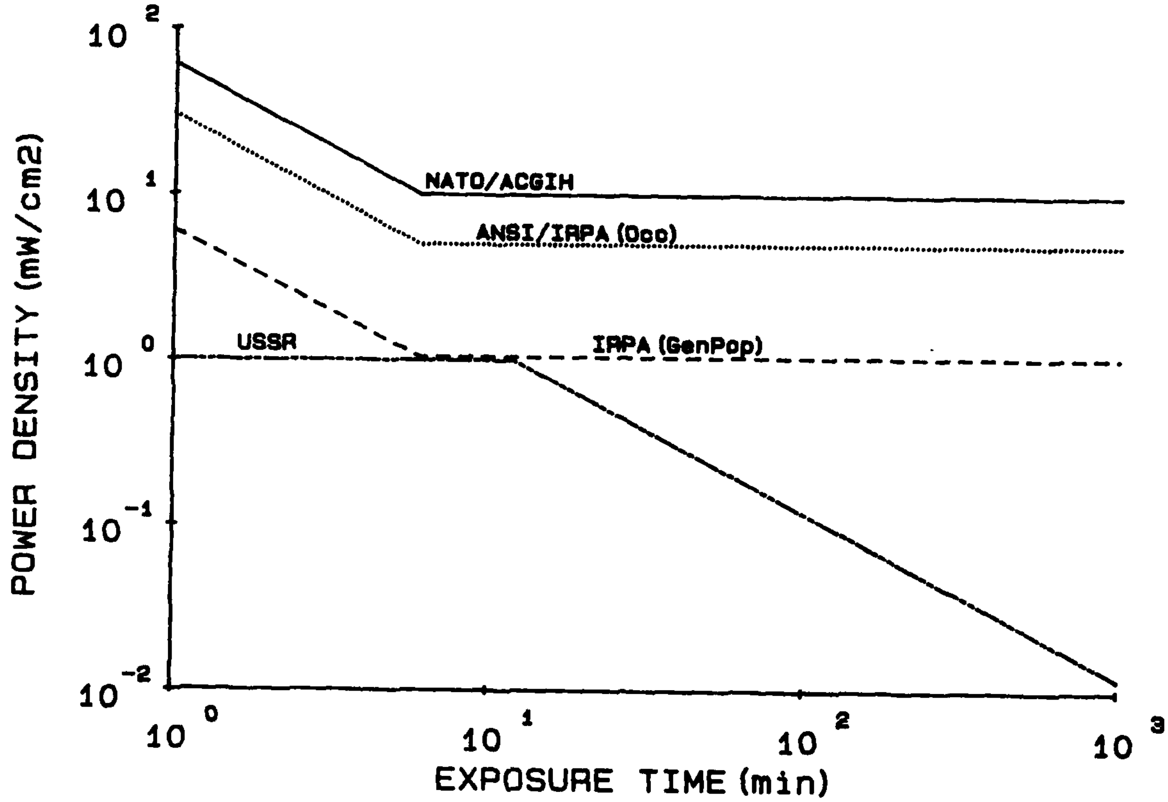

Figure 6. Power density vs exposure time (for frequencies >2 GHz).

TABLE 7
Comparison of RFR Exposure Limits (for Frequencies 30 MHz - 2 GHz)

	Power Density (mW/cm²)	Exposure Time(H)	Integrated Power Density (mW-s/cm²)	Specific Absorption Rate (SAR) (W/kg)	Specific Absorption (J/kg)
NATO	10	0.1	3600	4	1440
ACGIH	1	0.1	360	0.4	144
ANSI	1	0.1	360	0.4	144
IRPA (Occ)	1	0.1	360	0.4	144
IRPA (GenPop)	0.2	0.1	72	0.08	29
USSR	0.0066	2	48	0.0026	19

TABLE 8
Comparison of RFR Exposure Limits (for Frequencies >2 GHz)

	Power Density (mW/cm^2)	Exposure Time(H)	Integrated Power Density ($mW\text{-}s/cm^2$)	Specific Absorption Rate (SAR) (W/kg)	Specific Absorption (J/kg)
NATO	10	0.1	3600	0.4	144
ACGIH	10	0.1	3600	0.4	144
ANSI	5	0.1	1800	0.4	144
IRPA (Occ)	5	0.1	1800	0.4	144
IRPA (GenPop)	1	0.1	360	0.08	29
USSR	0.1	2	720	0.004	29
	1	0.2	720	0.04	29

Safety Considerations

The new RFR exposure guidelines have many built-in safety features that are rarely, if ever, considered. In these days all forms of radiation are often perceived as life threatening, so to highlight some of the inherent safety features associated with the new RFR exposure standards seems most appropriate.

SAR Versus Derived Incident Power Density

Many reviews of the RFR bioeffects literature have been written since 1980 (3,8,11,14,15). Based on these reviews, a whole-body SAR of 4 W/kg has been established as a reasonable value for the biological-effects threshold. Using a 10-fold safety factor, most new standards are designed to limit RFR exposures to a whole body SAR of 0.4 W/kg or less. In fact, most of the derived curves for permissible incident power densities provide more than a factor-of-10 safety. For example, the IRPA occupational exposure limit at frequencies above 10 MHz is 0.4 W/kg or less. The derived incident power density in the frequency range 10-30 MHz is set at 1 mW/cm^2; it could, in fact, range from 1 to 9 mW/cm^2, under worst case (physical contact with a ground plane) exposure conditions, without exceeding the 0.4-W/kg whole-body SAR. In the resonant region, the ANSI curve is actually closer to 0.35 W/kg than to 0.4 W/kg.

RFR Penetration and Absorption in Biological Systems

The vast majority of biological-effect studies that have been used to establish the current RFR safety guidelines were conducted using small laboratory animals (mice and rats) and 2450-MHz radiation sources. In such studies, the RFR energy is deposited throughout the animal's body and includes "hot spots" of RFR absorption that can be 10 to 20 times higher than the average. The 4-W/kg effects thresholds were established using worst-case data. The most likely human exposures are much less traumatic because the RFR energy is not generally deposited throughout the body. To illustrate this fact, Table 9 gives some approximations of the penetration depth in biological tissue and

the percent of total body mass (in humans) that might be exposed as a function of radiation frequency. Depth of penetration is defined as the distance at which the power absorption is e^{-2} (0.135) of the surface value.

TABLE 9
RFR Penetration and Absorption in Humans

Frequency of Radiation (GHz)	Depth of Penetration in Tissue (cm)	Percent of Total Body Mass Exposed
1	4.05	20.8
2	2.46	15.6
4	1.66	9.2
8	0.65	4.0
10	0.46	2.9
20	0.16	1.0

For example, a "standard" man exposed to a 1-GHz field might receive a unilateral exposure penetrating to a depth of ~4 cm and resulting in ~21% of the total body mass receiving RFR energy. For a 10-GHz exposure, the RFR energy might only penetrate to ~0.5 cm and result in less than ~3% of the total body mass receiving RFR energy. In fact, real-world exposure situations are much more complicated because the RFR energy is deposited in a very nonuniform manner, resulting in hot spots which are difficult to predict. These so-called hot spots do not relate to actual temperature excursions but to the fact that the SAR at different locations in the body can vary by an order of magnitude. Nevertheless, the data presented in Table 9 illustrate that in most exposure situations the RFR energy is deposited unilaterally in a relatively small volume of the body. In many exposure situations, an appreciable fraction of the body is not subjected to any significant energy deposition for exposures at or below the safety guidelines. This is believed to be an added safety factor when the potential bioeffects of RFR exposures are considered. Researchers recognize that the body's thermoregulatory system must still handle the total energy deposited, but such heat loads are less than one-half of the basal metabolic rate (BMR) for permissible exposure levels.

Partial Versus Whole-Body Exposures

Most human exposures at radiation intensities approaching the safety limits will result in only a part of the body being exposed. For example, most radar systems propagate radiation beams confined to a few degrees in both lateral directions, and depend on scanning to cover the surveillance volume. Human exposures at intensities approaching the maximum permissible values would normally occur only close to the source, where the beam size is relatively small. This situation also exists for exposures to the leakage fields from microwave ovens and from a wide range of RFR-generating equipment. Such partial-body exposures for frequencies greater than about 1 GHz at intensities which exceed the normal limits are often felt as a warming sensation, thus warning the person to terminate such an exposure before it becomes more serious.

Subject and Source Dynamics

The radiation protection guides applied over the frequency range covering whole-body resonant conditions were selected to protect the human under the worst circumstances (1,2,3,4). They assume the human would be exposed for 6 minutes to a free-space plane-wave field at the radiation frequency equivalent to his or her resonant frequency (dependent on the person's height), with the electric field vector aligned with the long axis of the body, and at the maximum RFR radiation intensity allowed by the guideline. These circumstances seldom, if ever, occur. For example, it is rare that a person would be in a field having his or her resonant frequency at the maximum intensity allowed. Even with a measured level equal to the maximum, the isodose intensity contour would not likely be as large as the human. Also, it is unlikely that the person would maintain an erect posture, particularly for 6 minutes at a time. Changes in posture such as stooping, bending, or squatting significantly reduce the RFR energy absorption. This point is illustrated in Figure 7, where relative power absorption curves have been plotted for a 1.8-m, 70-kg human who has changed his or her effective height by squatting, sitting, standing with arms in normal position, and raising the arms above the head. As in Figure 1, these curves were developed using prolate spheroid models with a constant body mass of 70 kg. In some jobs people might remain a fixed distance from an RFR source, but in most exposure situations there is considerable movement between the source and subject. Such movement often reduces the amount of RFR energy absorbed. Guy and Chou (16), using scaled models of a man and a 450-MHz source, measured the SAR and the SAR distribution for 12 possible field polarizations and 4 body postures; using a 1-mW/cm^2 exposure level, the mean SAR was about 0.05 W/kg and the spatial peak SAR was as high as 0.2, 0.6, and 0.3 W/kg for the neck, wrist, and ankles respectively. These results indicate almost an order of magnitude safety over that designed into the ANSI standard. Additionally, normal thermoregulatory response (blood flow) in living animals minimizes the temperature excursions predicted from static models (17).

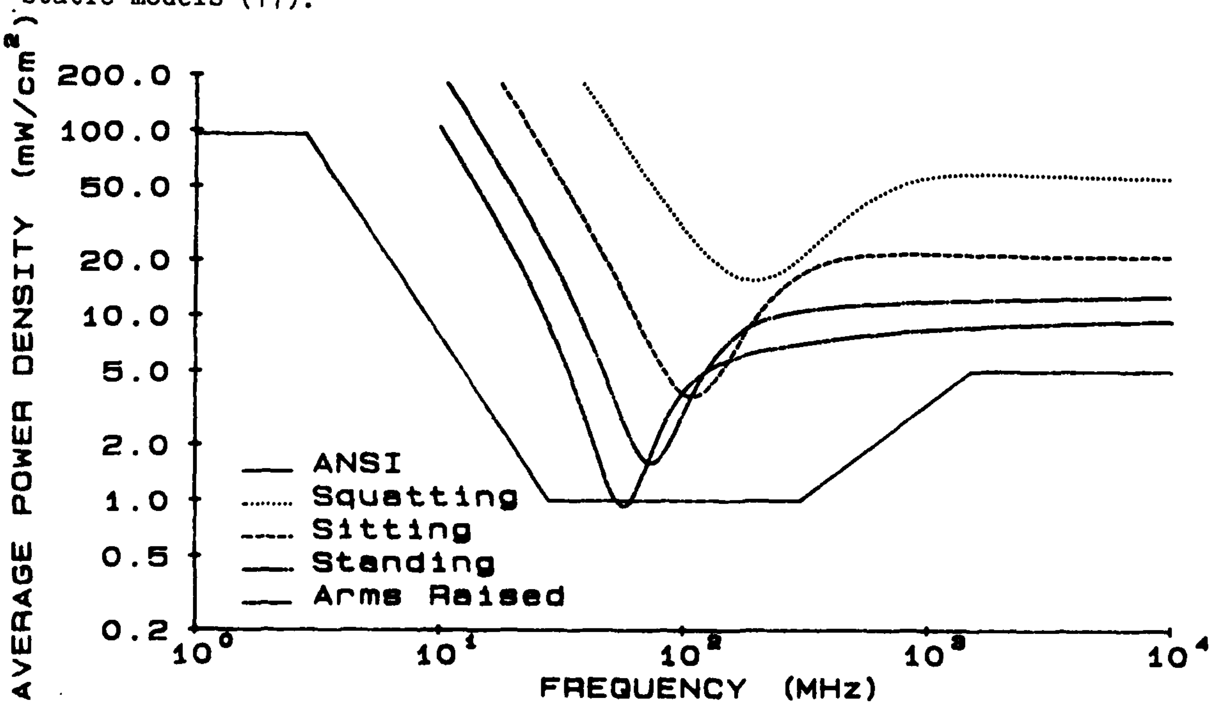

Figure 7. Power densities that limit human whole-body SAR to 0.4 W/kg for a 1.8-m person.

When the above facts are considered, it is hard to imagine any occupational setting today where all of the conditions would tend to maximize and maintain the RFR exposure for a 6-minute period. Thus some significant, albeit unquantified, additional safety factor is inherent in the application of these new guidelines.

CONCLUSIONS

Advancements in understanding RFR interactions with living systems, based on dosimetry and biological-effect research, are shared throughout the world. Differences in RFR safety guidelines established by different governmental bodies depend largely on the degrees of conservatism applied and philosophical approaches taken. These facts are well documented in current reviews of RFR-induced biological effects (3,4,8,15).

New research to assess biological effects of RFR exposure has emerged rapidly and in considerable quantity over the past 5 years. The vast majority of reported effects are related to thermal insults from incident average power densities greater than 2 mW/cm^2. When analyzed in terms of SAR as a common denominator, effects appear at threshold values near 4 W/kg. The new RFR safety guidelines and their rules of application clearly provide greater safety than those used in the past. They have a more credible scientific basis and are supported by the overwhelming majority of current research findings.

FUTURE TRENDS IN RFR STANDARD SETTING

The acceptance of whole-body averaged SAR in the development of the new frequency-dependent-RFR safety standards has been a significant improvement. It relates well to laboratory studies using small animals subjected to RFR fields at frequencies close to resonant conditions.

Despite these facts, whole-body SAR is not an adequate basis for the RFR safety guidelines at frequencies greater than 20 GHz and less than 3 MHz. At frequencies greater than 20 GHz, RFR energy deposition in biologic tissue is very superficial, as shown in Table 9, and some form of localized SAR would serve as a better safety guideline than a whole-body averaged SAR. New safety guidelines for the 20-300-GHz frequency range will likely emerge in the next few years.

Also, whole-body averaged SAR is not an adequate basis for safety guidelines below ~3 MHz since the RFR absorption in biologic tissue decreases as a function of frequency squared below the resonant point. The actual RFR energy absorption becomes so small in this frequency range (10 kHz - 3 MHz) that it can be considered safe at any practical value of incident power density. Valid questions remain, however, concerning the potential for shocks and burns. These questions are being studied under current research programs, and new safety guidelines can be expected in the next couple of years. Interim guidelines to avoid shock and burn are contained in the ACGIH TLV standard.

In summary, for the frequency range of greatest concern to present military RFR operations (3 MHz - 20 GHz), current safety guidelines based on whole-body averaged SAR are appropriate. Some refinements can be expected, however, as dosimetric methodology is improved and biological effects are better defined.

ACKNOWLEDGMENTS

Special appreciation is extended to Mr. William D. Hurt, Radiation Physics Branch, Radiation Sciences Division, U.S. Air Force School of Aerospace Medicine, for developing the information used in the tables and figures of this paper. We are also indebted to First Lieutenant Luis G. Lozano (deceased) for developing the computer programs used to generate the data base from which much of this information was selected.

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RESEARCH OPPORTUNITIES

I have noted above that I believe that future bioelectromagnetics research will have to place an emphasis on disclosing mechanism of interaction between electromagnetic fields and biological tissue. In Table 3 I have listed a series of research opportunities that I developed by identifying intriguing results published in the past several years. Although this is not the appropriate place to review the literature in this area, I would like to lend a sense of concreteness to this list by identifying some of the work that prompted me to draw up the list as I have.

TABLE 3. RESEARCH OPPORTUNITIES IN BIOELECTROMAGNETICS

1. ELF Pulsed H-Fields
2. ELF Pulse- or Amplitude-modulated RFR
3. Intensity Windows
4. Pulsed Fields, Peak Intensity
5. Pulsed Fields, Duration of Pulse
6. Synergism Between RFR and Other Factors
7. Resonant Field Effects

There is a rich literature on bioeffects of pulsed magnetic fields. Many of these studies have used waveforms identical or very similar to those used in clinical devices employed to aid in healing bones. To pick one set of the many studies in this area, I would choose those by Jose Delgado and his colleagues (1) in which they report significant alterations in development of chick embryos exposed to magnetic fields pulsed at less than 100 Hz, at maximum intensities no greater than a few gauss. One important issue that must be resolved is whether the magnetic fields themselves produce the effects, or are induced electric fields the important factor. The recent report by Liboff and coworkers (2) suggests that, contrary to the preponderant view, magnetic fields themselves are capable of altering basic cellular processes.

Miscellaneous Characteristics of the Quasi-Ideal Experiment

9. Determination of the effects of irradiation should not interact with the irradiation itself; that is, the observations should neither perturb nor be perturbed by the incident radiation. While in principle it is almost always possible to design an experiment to avoid such interaction, the practical difficulties are formidable. If real-time observations are required, then generally it is necessary to introduce an optical link between the preparation and the observer or to perform measurements on a portion of the organism that lies outside the field, otherwise the possibility of observational artifact cannot be discounted.

10. Experimental design should permit the experimenter to distinguish between thermal and athermal effects. Thus an effect which rises to a steady level in a time much less than that required to establish thermal equilibrium may tentatively be assumed to be athermal. When the effect is slower in onset, its origins can be probed by the use of shifts in such parameters of the incident field as modulation, carrier frequency, and polarization. For example, the thermal time constant of a watery sphere of radius "r" meters is on the order of $7 \times 10^5 r^2$ seconds; thus in a 1-mm structure, an effect that, at constant average power, varied with pulse repetition rate above 100 kHz, should probably be classified as athermal.

11. The experiment must be exportable. An experiment so demanding of technique or equipment or manpower as to be beyond the reach of virtually everyone is somehow lacking: the experiment should be simple enough to encourage replication by others.

12. The experiment should be seminal. It is not enough that an experiment be rich in insights and clearly point the way to scientific breakthrough, it must also be widely perceived to do so. And this, in addition to the lucidity, timeliness, and correct placement of the published results, also implies the existence of a populous scientific coterie familiar with both the preparation and most of the experimental techniques. It would seem that the wisest course to choose is to use a familiar preparation and familiar techniques, but to combine them in a novel though readily comprehensible fashion to yield results that are then placed in a widely read journal.*

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* The demands annunciated in this paragraph would seem to be great; but the returns should be enormous. I am put in mind of a passage written by Lewis Thomas in his book The Lives of a Cell: "There is nothing to touch the spectacle. In the midst of what seems a collective derangement of minds in total disorder, with bits of information being scattered about, torn to shreds, disintegrated, deconstituted, engulfed, in a kind of activity that seems as random and agitated as that of bees in a disturbed part of the hive, there suddenly emerges, with the purity of a slow phrase of music, a single new piece of truth about nature."

One of the individuals I asked to review this manuscript before I presented it said of this paragraph: "Bull! Some of the best science is not believed by the vast majority until they are hit in the head with it." My point exactly!

2. There should be substantial control over both the frequency of the irradiation and its modulation. This implies both that some care be given to matching source and load and that the source itself be flexible. Although in situations where very high peak power densities are sought these may be achievable only with specialized pulse units, in most cases it is probably best to proceed using flexible frequency sweepers with AM capability, PIN modulators, and broad-band power amplifiers.

Biological Characteristics of the Quasi-Ideal Experiment

3. The biological preparation should be well understood. "Well understood" is, of course, a relative term; but at the very least there should be an extensive literature on the properties of the system. For example, the nemertine flame bulb is less desirable than the slime mold physarum polycephalum (one of my favorites), and less desirable than a giant squid axon.

4. The biological preparation should be both robust and stable. Chronically feeble preparations derived from difficult-to-culture organisms will tend to divert the experimenter's attention from the experiment. It is also true that finicky preparations, which demand extreme control of experimental parameters before yielding up the desired data, frequently generate more uncertainty than they dispel. And finally, it is clear that preparations whose relevant properties show undue stochastic variation can divert the experimenter from the pursuit of understanding, to the pursuit of the replicate experiments needed to reduce the standard error of the mean.

5. The biological preparation should encourage penetration to deeper levels of understanding. When the experiment at hand is successfully completed, it should be fairly obvious which next step is most likely to deepen one's understanding of the phenomenon and the causative mechanisms underlying it. A "successful" experiment, which yields no clear hints as to what might profitably next be done, is not truly successful.

6. The biological preparation should provide for amplification of a radiation-induced effect. The initial transduction events may easily be so small as to go undetected despite a highly sensitive assay. If, however, they give rise to a cascading sequence of changes in the physiology, development, or behavior of an organism, their existence may eventually become manifest.

7. The properties of the preparation chosen for study should be unambiguously and precisely quantifiable. Whenever possible, subjective judgments of "more" or "less" or "anomalous" should be replaced by accurate numerical comparison. This reduces the effects of experimenter bias and increases the prospects of detecting small changes in physiological function.

8. The experiment should encourage both control and data analysis in real time. Experiments whose results cannot even be guessed at for many days frustrate attempts at extensive and informed variation of experimental parameters. Such variation is likely to be of great importance in any attempt to ferret out the bases for an effect.

TABLE 2. CHARACTERISTICS OF THE QUASI-IDEAL BIOELECTROMAGNETICS EXPERIMENT

<u>Electromagnetic Characteristics of the Quasi-Ideal Experiment</u>

1. Fields present within the biological preparation should be approximately prescribable, or the power absorbed should be approximately prescribable.

2. There should be substantial control over both the frequency of the irradiation and its modulation.

<u>Biological Characteristics of the Quasi-Ideal Experiment</u>

3. The preparation should be well understood.
4. The preparation should be robust and stable.
5. The preparation should encourage penetration to deeper levels of understanding.
6. The preparation should provide for amplification of a radiation-induced effect.
7. The preparation properties should be unambiguously and precisely quantifiable.
8. The experiment should encourage both control and data analysis in real time.

<u>Miscellaneous Characteristics of the Quasi-Ideal Experiment</u>

9. Determination of the effects of irradiation should not interact with the irradiation itself.

10. Experimental design should permit the experimenter to distinguish between thermal and athermal effects.

11. The experiment must be exportable.

12. The experiment must be seminal.

HOW DO WE GET THERE?*

Although there are now a considerable number of reports in the literature of bioeffects of nonionizing electromagnetic irradiation that are thought to be athermal in nature, there are few wide-ranging experiments and little firm theory which may be used either to elucidate the causative mechanism of such effects or to guide future experimentation. Bioelectromagnetics research is hampered both by a prevalence of results of uncertain interrelationship and by a shortage of well-defined and clearly informative avenues for future investigation.

The reasons for these shortcomings are varied, but at least some of the blame can be laid to the suboptimal choice of both biological preparation and irradiation system. There exists a widespread tendency to choose both the biological preparation and the irradiation system because of local familiarity and perceived institutional or financial constraints.

General Observation 4: **Exposure systems often dictate either the objective or protocol of an experiment.**

In my judgment it is all too common to find an inadequate expenditure of effort to define the characteristics of a quasi-ideal experiment and then to search out biological preparations and electromagnetic configurations which might approximate it. The proper order for design of experiments is (1) to begin by defining the objective, (2) selecting appropriate subjects, (3) designing exposure systems, and last but not least, (4) adopting correct statistical procedures for analysis of data. In the remaining portion of this section I will focus on items (2) and (3) by outlining criteria for the quasi-ideal experiment. Let me reverse the order of importance of topics and begin by discussing exposure systems. (Table 2 presents an overview.)

Electromagnetic Characterization of the Quasi-Ideal Experiment.

1. The field present within the biological preparation should be approximately prescribable; alternatively, the power absorbed should be approximately prescribable. Thus, an organism wandering in the near field of a horn antenna is less desirable than an organism fixed in the far field of a horn, is less desirable than an organism constrained in an air-filled waveguide, is less desirable than an organism placed in a matching dielectric medium and sandwiched into a microstrip. It is probably not necessary to know and to control irradiation to ± 0.2 dB; but it is desirable to hold the local SAR within ± 3 dB as the frequency is shifted over an octave.

*In preparing this section I have drawn liberally from a proposal submitted to the ONR by William Pickard from Washington University in St. Louis. Professor Pickard and I first discussed the ideas presented here at a workshop on non-linear wave phenomena held at the University of Maryland in November 1983.

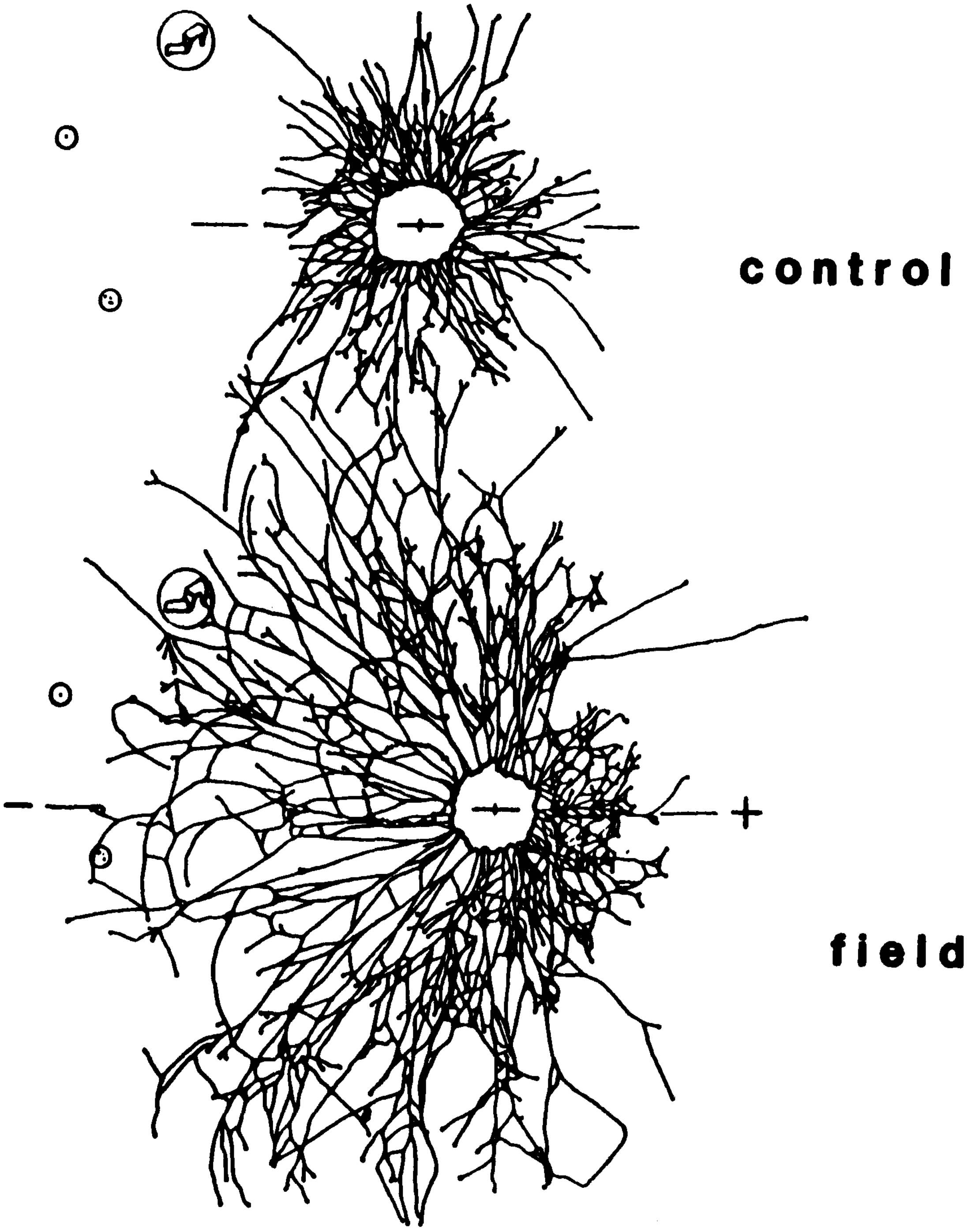

Figure 2. Neurite outgrowth is enhanced and directed by weak electric fields of 70 V/m. Neurites are the dendritic outgrowths that must occur during regeneration of a nerve. Nervous tissue has very limited natural capacity for self-regeneration. L.F. Jaffe and M.-M. Poo, J. Exp. Zool. 209:115-128 (1979).

From my perspective the most important questions still to be answered are the basic science questions. Just how in the world do weak electromagnetic fields interact with cells and tissue? Is it possible to use electromagnetic fields to probe cell function with a kind of cellular "spectroscopy"? Will we be able to alter or otherwise control cell function using electromagnetic fields? There is every reason to believe that the beneficial applications of electromagnetic fields will dominate our research focus sometime in the next ten years. Cell growth and differentiation processes associated with tissue repair are known to be regulated by the electrochemical environment of the tissue cells. There is also an abundance of laboratory and clinical data to demonstrate that electromagnetic fields can directly influence cell behavior. With additional understanding of these environmental factors, we should be able to enhance natural processes involved in healing and dealing with disease. One dramatic example of this type of influence is shown in Figure 2 which illustrates how low-level dc electric fields can both enhance neurite outgrowth and control the direction of growth. The medical implications of this type of control are tremendous.

WHAT TO DO NEXT?

I think the answer to this question is simple: we must emphasize work on mechanisms.

General Observation 3: **Future bioelectromagnetics research must emphasize mechanisms of interaction.**

I don't mean to suggest that we should abandon all other research efforts. In particular I believe that it is necessary to continue a vigorous program of whole-animal research that will build a basis for more sophisticated assessment of hazards. Hazard assessment is at best a political process in the sense that firm conclusions must be drawn from partial information. There is a good chance that the riddle of the mechanism by which electromagnetic fields interact with biological tissue, in all its complexity, will not be solved in the very near future. Thus we will continue to require additional information on which to base our judgments and decisions. Incomplete animal-based information is very likely to be more useful in this exercise than is incomplete cellular or molecular information; or for that matter, a partially verified theory.

The work on mechanisms must involve interdisciplinary teams, and we must find ways of attracting "world-class" scientists and engineers to undertake the effort. I don't believe I am overstating the issue when I say that the future funding of basic research in bioelectromagnetics is at stake. Although I find it somewhat painful to admit, our area of endeavor does not enjoy the highest standing amongst our research colleagues in other areas. One might take the view that this is a logical consequence of my first two axioms: the research requires considerable sophistication both to conduct and to interpret; and most of the research cannot be traced to a few central hypotheses which might make approaches easier to grasp. The wide variety of bioeffects that have been reported, and the frequent lack of confirmatory or followup experiments, presents a bewildering picture to those not completely familiar with the history of bioelectromagnetics research.

This research has led to development of many useful clinical devices and has laid the groundwork for the recent and current efforts at establishing safety standards that were described in detail in an earlier presentation. In our view this type of phenomenological research was entirely appropriate for a new field of research like bioelectromagnetics, especially given the urgent need to respond to the demand for safety standards. The standard setting process has pointed to the type of research that will be needed in the next decade if we are going to be able to deal responsibly with the many different questions raised by research in the past decade.

QUESTIONS LEFT UNANSWERED

The standard-setting efforts have raised a number of important questions that require answers before the next round of standard-setting can be undertaken. While regulators generally agree today that the best single measure of exposure for standards is the average SAR (specific absorption rate), there are reasons to believe that other measures might be more appropriate in some instances. The existence of intensity windows and resonance effects (frequency windows) strongly suggests that some effects do not depend on the rate or amount of energy absorbed but on the way in which it is packaged. Other investigators have raised the question of whether instantaneous SARs or maximum field levels might not be a more appropriate variable for some types of biological responses.

"Windows" are not new to biology. The existence of competing processes can result in a window. A commonplace example of this phenomenon is the dependence of cell growth on temperature. As temperature increases, the growth rate increases steadily because the biochemical reactions required for growth proceed more rapidly. As some optimal temperature is passed, the growth rate begins to decrease as other competing processes, like the denaturization of proteins, become more important. However, the existence of multiple windows cannot be explained as a simple competition between two processes, and more complex explanations must be invoked. The existence of window effects has important implications for the development of safety standards. Development and testing of medical devices present another area in which windows may be exploited and need to be understood in order to insure safe operation of the devices.*

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* Portions of this paragraph were taken from the book Handbook of Biological Effects of Electromagnetic Fields edited by C. Polk and E. Postow from a chapter entitled "Modulated field and 'window' effects" written by Elliot Postow and Mays Swicord (CRC Press, Boca Raton, Florida 33431, 1984).

A partial explanation for this phenomenon, at least at ONR, is that we have increased our emphasis on mechanistic research. Biological scientists are not as comfortable with quantitative experiments as physical scientists. No doubt there are other, less generous, interpretations of this phenomenon. Nevertheless, I am of the opinion that the phenomenon is widespread, and becoming more exaggerated. One interpretation of this situation, that I will expand upon below, is that the interdisciplinary nature of bioelectromagnetics research coupled with the past emphasis on hazards has caused the best biological scientists to focus their energies elsewhere. Whatever the cause, I view the need to attract first-rate biological scientists to research in this field as one of the most pressing items on the agenda for funding agencies.*

WHAT HAVE WE LEARNED?

By far the principal motivation for bioelectromagnetics research has been a concern for hazards, which leads me to a statement of my second general observation:

> General Observation 2: **Bioelectromagnetics research has been phenomenological.**

While this is not universally true, like the previous observation it is a fair generalization. Thus a great deal of research has been aimed at discovering bioeffects (or establishing the absence of effects) for given frequencies and waveforms; when effects have been observed attempts are sometimes made to measure a threshold for effects, that is, a lower value of field intensity below which experimental outcomes are different. The balance of bioelectromagnetics research has been distributed between (1) research and development for clinical devices such as hyperthermia devices, (2) fairly basic research efforts to characterize dielectric properties of tissues, and (3) engineering projects aimed at determining how energy is absorbed in subjects exposed to fields of different geometry, frequency, and orientation.

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* An alternative view of this problem is that biologists do not feel comfortable in addressing problems outside those narrowly defined as biological in nature. On the other hand, physical scientists will approach any problem with the belief that problems outside their own specific area will yield once the language of the new field is assimilated. I am reminded of a letter that appeared in Physics Today some time ago written by physics Professor Goodstein from Cal Tech, in which he said: "It is the feeling physicists have that in a fundamental way they understand everything. Add a few messy details and you get chemistry, a few latin names and you get biology, but at the core it all reduces to physics. By and large, only the physicist will walk fearlessly into any seminar, only the physicist takes all of science for his domain." The point I wish to make here is that the problem of bringing more biological expertise to bear in this research area may be partly a psychological one. We (physical scientists) must learn to appreciate the difference in approach that biologists bring to research.

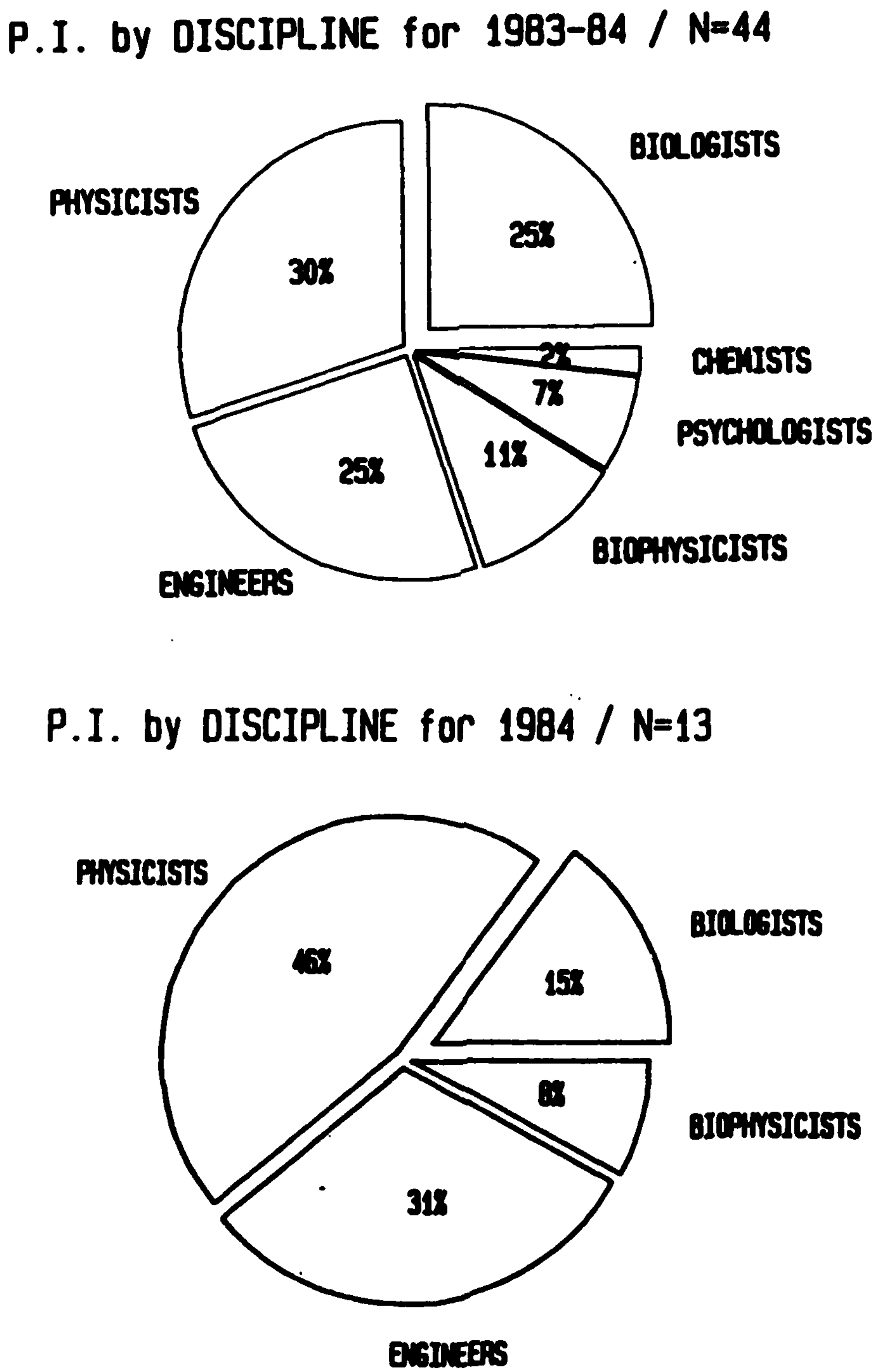

Figure 1. Contract awards broken down by discipline of principal investigator.

PLAYERS: The Researchers

In Figure 1 is given a breakdown by discipline for researchers funded over the past year in the ONR Bioelectromagnetics Program. Also shown is a separate discipline breakdown of investigators on contracts awarded in the past six months. I will refer to this second breakdown shortly, but for the moment focus your attention on the upper pie chart. I believe that the data in Figure 1 are representative of researchers working throughout this area of research, which brings me to state the first general observation concerning bioelectromagnetics research:

General Observation 1: **Bioelectromagnetics research is interdisciplinary.**

While I am sure that many of you will not find this observation particularly surprising, it is extremely important to keep in mind that in order to conduct bioelectromagnetics research it is almost always necessary to assemble a team of scientists balancing biological or psychological expertise with individuals from the physical and engineering sciences.

Interdisciplinary teams must be true teams with shared responsibility for planning and conduct of experimental (or theoretical!) work. The engineers cannot participate as electronics technicians; their expertise and understanding of electromagnetic fields is absolutely necessary to the design and analysis of worthwhile bioelectromagnetics experiments. Moreover, biologists cannot be involved only as a pair of hands for preparation of tissue samples or for feeding organisms. Their insight into the physiological significance of experimental phenomena is, unfortunately, all too often lacking.

Many of us can point to examples of engineers who have conducted classic experiments in bioelectromagnetics with little or no assistance from biologists; and there are even a few examples of the reverse situation where a biological scientist has produced good research working alone. But these instances are, in my opinion, the exception. It pains me to think how much money we have spent teaching elementary biology to engineers and physicists working alone, or conversely, teaching biologists the basic physics and engineering principles necessary to do research in this area. Not only is this an extremely inefficient use of funds, it is in most cases a complete waste. Major advances in understanding today <u>require</u> an interdisciplinary approach at the level of design, conduct, and analysis of experiments. A similar but somewhat weaker statement can be made about development of theories for interpretation of experiments.

One additional feature of the data in Figure 1 that I wish to draw to your attention is that only 25% of bioelectromagnetics research is conducted by scientists trained in the biological sciences; and this figure appears to be declining. Data are shown in the lower pie chart of Figure 1 for contracts awarded by the ONR Bioelectromagnetics Program during the past six months. Although the total number is small, it is representative of a far larger total number of proposals and preproposals we have received in the past six months, but which have not been funded.

TABLE 1. U.S. AGENCIES SUPPLYING FUNDS FOR EXTRAMURAL BIOELECTROMAGNETICS RESEARCH. DOD FIGURES ARE FISCAL YEAR 85 FIGURES.

Department of Defense	Navy	4.5 M$
	Air Force	3.2 M$
	Army	2.4 M$
Health & Human Services	Center for Devices and Radiological Health	0.25 M$
	National Institutes of Health	1.0 M$
Environmental Protection Agency		1.0 M$
Department of Energy		4.0 M$
Electric Power Research Institute		3.0 M$
New York State Powerlines Project		2.0 M$

The last three entries in the Table (Department of Energy, Electric Power Research Institute, and New York State) are supporting work that is primarily concerned with the effects of electromagnetic fields associated with power transmission lines; a portion of the Department of Energy budget is assigned to bioeffects of intense dc magnetic fields. Since much of this research is not of direct interest to those concerned with radiofrequency field effects, I will have little to say about these efforts in the remainder of my presentation. It is interesting to note, however, that nearly half of the total funds budgeted for research in bioeffects of electromagnetic fields is devoted to transmission line fields. This is a fairly recent phenomenon; five years ago this figure was smaller by an order of magnitude.

It is of some interest to speculate on what has been the cumulative total expenditure of funds in this area of research. Without too much exaggeration one could argue that serious scientific research on bioeffects began sometime in the late 1940's with the work of Herman Schwan and his colleagues at the University of Pennsylvania. However it was not until the early 1960's that a reasonably large group of workers could be said to exist. In the 30 odd years of research in this area, I guesstimate that 200 M$ has been spent on research. An obvious next question is what has this expenditure bought us? The answer is quite a bit. In the next two sections I will attempt to characterize the researchers who are working in the area and briefly summarize their findings.

INTRODUCTION

In this presentation I hope to outline for you my vision of the future for research in the area of bioeffects of radiofrequency electromagnetic fields. I will of course draw upon my experience at the Office of Naval Research, but I wish to emphasize at the outset that the opinions I express are my own and are not necessarily shared in their entirety by my colleagues in the Navy.

I will begin by giving you a quick overview of how research is funded in this area and then attempt to summarize where we have been, before I begin my description of where we are headed. I have some thoughts on how we should approach the future that I would like to share with you, and I will close by giving you a list of the pressing questions that require attention by all of us. I call this list "Research Opportunities" and I hope that, by the end of my presentation, you will share my view of this list of unanswered questions as being a list of opportunities.

PLAYERS: The Funders

In Table 1 I have identified the agencies in the United States that are responsible for funding the bulk of research involving the interaction of electromagnetic fields with living organisms or biological tissue. The dollar figures next to the agency name are my best estimates of the current budget for research in this area. These figures must be viewed with some caution for, besides being somewhat uncertain, they include a variety of different types of activity lumped together under the heading of bioeffects research.

The Department of Defense figures are probably the most accurate figures in the table. These figures include basic research on mechanisms of interaction, research on techniques for estimating exposure and dosage for various frequency ranges, and work on clinical imaging techniques that make use of non-ionizing radiation. The estimate for FDA includes funds for an epidemiological survey of workers using radiofrequency sealing equipment. NIH has two programs supporting research on bioeffects: the Institute of Environmental Health Sciences supports basic research related to hazard assessment, and the Institute of Arthritis, Diabetes, and Digestive and Kidney Diseases (lovingly known as NIADDKD) supports research aimed at understanding how electromagnetic fields affect the growth and structure of bone and cartilage. EPA, NIEHS, and the Center for Devices and Radiological Health all have substantial in-house programs of research in this area. NIOSH, the National Institute for Occupational Health and Safety, has no extramural program at the present time but has under consideration an epidemiological study. I have not included funding for these intramural programs in Table 1.

RFR RESEARCH PROJECTIONS FOR THE FUTURE

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I would also like to note why I have included low-frequency pulsed magnetic field experiments in a presentation dealing with radiofrequency fields. Delgado's most recent studies suggest that the onset time of his pulses is crucial to producing a biological response. Pulses with rise times of 40 μs were far more effective in producing effects than were pulses with rise times of 100 μs. It is interesting to note that the 40-μs pulses were also more effective than pulses with 2-μs rise times, suggesting a "window" for responses. A fourier decomposition of the waveform used in these experiments would produce results with many similarities to a decomposition of appropriate low-frequency pulsed RF radiation.

ELF modulated RF fields have been reported to affect a number of physiological functions in instances where the unmodulated fields have no effect. Bawin and her colleagues (3) demonstrated that VHF fields modulated at certain frequencies, similar to brainwave frequencies, could alter electroencephalograph (EEG) patterns in the cat. Takashima (4) demonstrated similar changes in the rabbit EEG, using 1 to 10 MHz radiation modulated at 15 Hz. Bawin et al. (5) and Blackman and his colleagues (6) have also reported that amplitude-modulated RF radiation alters calcium ion efflux from brain tissue only within selected ranges of frequency and intensity. The intensity windows vary with frequency of the carrier wave. Very recently Blackman and his colleagues have discovered that the earth's own dc magnetic field may influence the manner in which organisms respond to alternating fields. They have shown that the calcium efflux frequency windows for neuronal tissue depend on the ambient magnetic-field strength in a surprisingly sensitive way (7).

The U.S. Environmental Protection Agency has recently begun efforts to prepare RF radiation exposure standards for the general population. The committee charged with reviewing their efforts recently noted in its summary of areas deserving additional research that the effects of exposure to pulsed sources of very high peak power might be different from those produced by waveforms of identical average power but lower peak power. The scientific issue underlying their concern was whether mechanisms for interaction exist that depend only on the field intensity and not the average power level. This same committee identified the potential for synergistic interaction between RF energy and other physical or chemical agents as another area for concern. I have entered both these areas in the list of research opportunities and note that there already exists evidence for synergistic action of RF fields with drugs (8) and alcohol (9).

Another rather different approach to bioeffects has been pursued by Wachtel and Barnes at the University of Colorado (10). They have both experimental and theoretical evidence demonstrating that pulse width of pulse-modulated microwave fields is an important variable. They have shown that a single microwave pulse of duration longer than a few microseconds (1) can elicit neural and behavioral responses that cannot be explained in terms of total temperature rise but can be predicted by models based on field detection or thermal rise rate mechanisms. They argue that it is not the amount of energy put into the system or the total temperature change that occurs that is important, but rather the rate at which the energy is put into the system that governs whether or not an effect is produced.

Last but not least in my list of research opportunities is resonance absorption of RF radiation by biological preparations. By resonant absorption I mean that an observed effect is strongly dependent on the frequency of the incident radiation. In the last few years a fairly large number of such effects have been reported. Perhaps the most widely known are the experiments of Grundler and Keilmann (11) in which they discovered that the growth rate of yeast can be either increased or decreased by as much as 10% when exposed to radiation in the neighborhood of 42 GHz, and that the change between increase or decrease occurs over a very narrow band of about 8 MHz. Statistical analysis of their data also revealed the existence of sideband satellites in the growth response curve plotted as a function of frequency of incident radiation.

Very recently scientists working at the Center for Devices and Radiological Health have reported observing resonant absorption of microwave energy in the 0.5-10-GHz region of the spectrum by solutions of DNA fragments (12). These workers see a series of absorption peaks which they interpret as fundamentals and higher harmonics; the position and spacing of the peaks is very strongly dependent on the chain length of the DNA in solution. At least as important as the observations themselves is the fact that these observations are fully consistent with the vibrational mode calculations of Prohofsky and Van Zandt from Purdue University, thus holding out the prospect that we may soon be able to interpret at least one interaction mechanism on the basis of first principles. The importance of such a development is difficult to overstate. Most current views of how biomolecules function are based on static, structural considerations. Because of the lack of detailed information the dynamical features of macromolecules have been ignored. We share the view of many that this oversight seriously limits the way we conceive biological processes on a molecular level.

CONCLUSION

My review of where we have been and where we are going in the field of bioelectromagnetics research leads me to conclude that research into the mechanism(s) by which electromagnetic fields interact with biological tissue will assume increasing importance in the next few years. Those concerned with assessment of hazards of nonionizing radiation require more information concerning mechanisms before they can proceed with their activity. However, the major new impetus for mechanism research will be derived from beneficial applications of electromagnetic fields to biological tissue. Use of electric and magnetic fields to promote healing is already widespread and will continue to increase. Every indication I can discover strongly suggests that the use of electromagnetic fields in the practice of medicine has only just begun. Advances in our understanding of how electromagnetic fields interact with living tissue will be followed rapidly by new techniques and devices for probing and controlling cell function.

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THE CUMULATIVE EFFECTS OF LONG-TERM EXPOSURE TO LOW LEVELS OF RADIOFREQUENCY RADIATION (RFR)

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INTRODUCTION

One primary concern about nonionizing radiofrequency radiation (RFR) has been accumulation of subtle injury over a long period of time, resulting in a delayed expression of harmful effect. Over the past 15 years this concern has been more vocally expressed, and various official bodies have identified long-term low-level effects as a main research priority (1,2). This unresolved issue has had considerable effect on the entities of government and industry that operate RFR emitters (3,4). By necessity, transmission exposes both operational personnel (occupational) and members of the general public (environmental). The responsibility for ensuring the well-being of the exposed population has gone from the entity producing the exposure to specific government agencies. The philosophical rationale for the exposure and the ingredients of the risk-benefit equation also change. These factors, through their effect on standards and permissible exposure limits, combine to affect the siting and mode of operation of any given emitter. The larger the degree of uncertainty, the more inclined standard-setters are toward extreme conservatism since the level of risk cannot be even roughly bounded. This is particularly true if one applies the reasoning underlying ionizing radiation permissible exposure levels (PELs)--that any level of exposure produces some injury, i.e., a linear extrapolation to zero.

In the case of RFR, a general consensus has been achieved among standard-setters that, for acute exposures, the threshold for ill effects lies above a specific absorption rate (SAR) of 4 W/kg (5,6,7,8). Since hazard (injury) has been verified only above this threshold, one might conclude that the current approach of applying a safety factor of 10 or more to this level would adequately protect the population at risk. Unfortunately this is not the case. Lack of data derived from true long-term experiments or from epidemiological studies of defined exposures to a human population has prevented a consensus from being reached for these kinds of exposures. In 1978, the U.S. Air Force, with the University of Washington, embarked on the most ambitious long-term low-level RFR study ever attempted. After 2 years of facility and equipment design, exposure device construction, protocol development and refinement, and pilot operation, a definitive study was initiated in September 1980. After 25 months of continuous exposure, the test was completed in September 1982. Data analysis and tissue examination were completed 1 year later, and the results are being published in a series of nine technical reports, of which the ninth is an overall summary and interpretation (9-17).

DOSIMETRY AND PROTOCOL

Background

Prior to the Air Force/University of Washington study, literature reports of long-term studies were quite diverse, with the definition "long-term" or "chronic" being applied to experiments involving exposures for a few hours during a time course of days or weeks. Before 1977 the reports were also hampered by inaccurate or missing details of the dosimetry methods used. Lack of a common denominator, such as the SAR, made comparisons among experiments from different laboratories difficult. Endpoints measured also varied widely, with the selection usually determined by the investigator's field of training

or interest or by using tests most readily performed. This lack of specificity produced conflicting and unrelated data sets, e.g., a few hematological parameters, a behavioral task, an immunological test.

To address these deficiencies, the Air Force/University of Washington study was conceived as a controlled study of the state of health of a test population large enough to yield statistically valid data. An identically treated population, except for the exposure, was also provided for.

Facilities and Procedures

The details of the experimental design, special facilities, and routine procedures are contained in Volume 1 of the final report series (9). They were also presented to the 1981 Panel VIII, RSG2 meeting at Farnborough in 1981 (18). To summarize briefly, several salient points should be emphasized.

Exposure Criteria

The first decision required was to select a test animal and exposure situation to best model the exposure of humans to 450 MHz. The 450 MHz was selected as the frequency of interest based on two main facts. Public concern had been expressed over the operation of a phased array radar (PAVE PAWS) which operates with frequencies in this region. Also, this frequency produces in man a whole-body exposure that is reasonably well distributed. When scaled to the rat, this equates to a frequency of 2450 MHz. Selection of a circular waveguide system and the Sprague-Dawley rat for the experimental system allowed a large number of animals to be exposed to a common RFR source while relatively constant and quantifiable electromagnetic coupling was independently maintained to each animal, regardless of location, posture, or movements. It was then necessary to choose a modulation frequency and the pulse parameters. Both selections were to some degree arbitrary but were based on the same concept used to select the basic 2450-MHz exposure frequency--namely to simulate in the rat the same distribution and absorption pattern predicted in humans from exposure to a typical midrange Air Force system. The modulation pattern chosen, 8 Hz, represented the dominant electroencephalogram (EEG) frequency of rats (19) and was included to encompass a reported effect of RFR exposure in vitro (20,21). These variables were arbitrarily fixed to limit the magnitude of the project.

The exposure system was characterized by exhaustive dosimetry, not only to ascertain the true pattern of energy absorption and distribution in the exposed subject but also to maximize the extrapolation of the findings by scaling the exposure frequency and intensity to represent human exposure to comparable conditions.

Biological Assessment

Considerable effort was made to select endpoints reflecting not only biological effects previously reported from low-level microwave exposure (e.g., alterations of hematopoetic, immunologic, and specific blood chemistry indices), but also possible cumulative effects on general health, metabolism, or lifespan. Only those endpoints were included that could be assessed without seriously compromising the health of the animal, the value of concurrent

measurements, or the power of the statistical evaluations. Peer review by researchers within the community concerned with the bioeffects of microwaves, as well as the scientific community at large, tempered the final protocol.

The endpoints selected fall within five general areas: (1) behavior, (2) immunology, (3) hematology and serum chemistry, (4) growth and metabolism, and (5) longevity and cause of death. Although treated separately to facilitate timely publication, the results are all interrelated--not to be treated as isolated experiments. Volume 9 (17) addresses the overall study and makes the proper cross-correlations among endpoints.

Behavior

The sole behavioral endpoint included as part of the overall protocol was an assessment of open-field activity. It was chosen after a variety of suggested behavioral tests--including shuttlebox avoidance, activity wheel, discriminated T-maze, and various schedule-reinforced, bar-pressing paradigms--had been evaluated according to the following criteria.

First, the behavioral test selected should not jeopardize the health of the animals and thus interfere with the primary goal of the project, i.e., evaluation of the status of health throughout life and effects on mortality. Second, the test should not lead to obvious reactions to stress or differential experience (e.g., shock density), based on level of performance during testing. Third, the test must be easily performed within the confines of the specific-pathogen-free (SPF) facility and the time schedule of the daily maintenance procedures. Fourth, the test must not be subject to bias on the part of the experimenter. Finally, the test must have a history of reported sensitivity in microwave-exposure studies.

The open-field test is not the most impressive of the behavioral test procedures considered, but it satisfies the selection criteria. It is simple in nature, does not rely on elaborate or time-consuming training procedures or shock-motivated performance, and can be routinely administered by laboratory personnel under the rigors of SPF control. East European researchers have used the open-field test extensively in studying the bioeffects of microwaves. Their reports claim that it is the most sensitive of the behavioral tests used, revealing complex relationships between observed behaviors, length of exposure, and power density (22,23).

Assuming behavioral changes could be stress related, corticosterone was periodically assessed for two purposes: (1) to monitor the general environment of the experimental animals and the handling procedures required by the daily maintenance schedule; and (2) to test specifically for corticosterone changes resulting from microwave exposure (24).

During the first year of the project, five corticosterone sampling sessions were completed, at 12-week intervals--coincident with every other regularly scheduled bleeding session. During the second year, corticosterone assays were made only twice--6 weeks before and at the time that the last surviving animals in each group were killed.

Except for the first assessment period, corticosterone values, open-field activity, and corticosterone levels were not significantly altered by 2 years of exposure to low-level pulsed-microwave radiation (12). A statistically

significant elevation of serum corticosterone was present in the first set of samples. This could have been due to random fluctuation, or the animals may have detected the exposure. In subsequent samplings there were no differences (Figure 1).

Immunology

Studies have been published concerning the immunological responses of various experimental animals to microwave irradiation. These studies provide a basic framework for inquiry but, when viewed as a whole, reveal inconsistencies and inadequacies that stimulate controversy concerning the significance of basic findings with regard to potential hazard to human health. Stimulatory effects indicated by the results of some studies have not been reproduced in others.

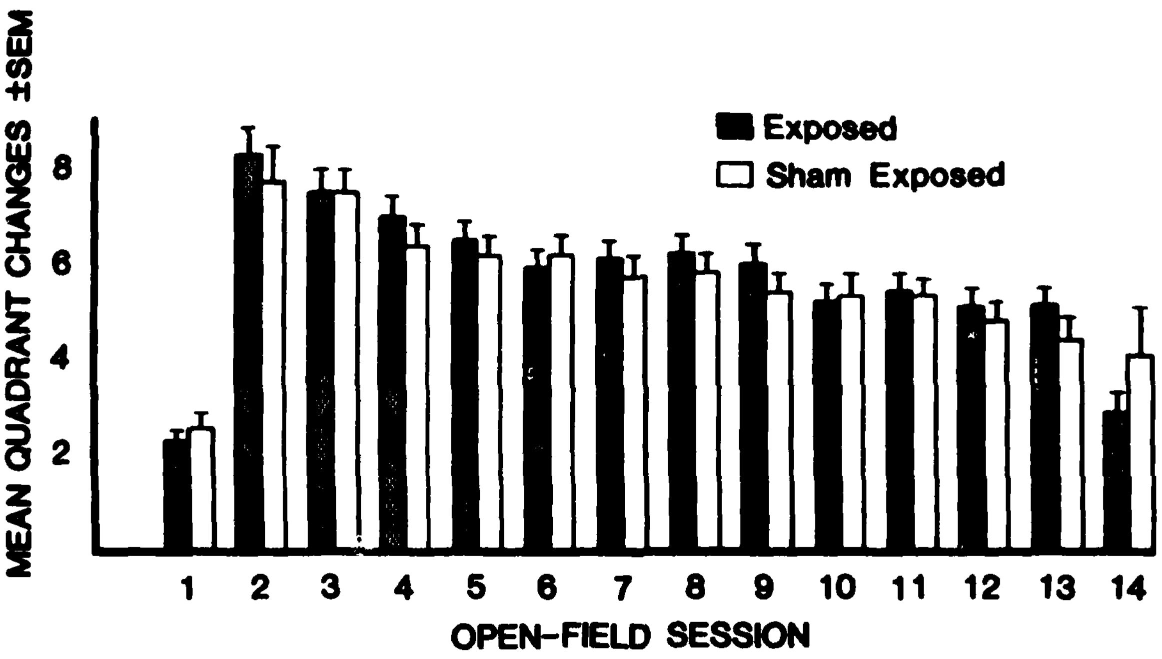
To examine this area of interest, the following immunological tests were performed coincident with the interim killing of 10 animals from each treatment group after 12 months of exposure: response of splenic lymphocytes to various mitogens, plaque-forming ability, complement-receptor formation, and enumeration of B- and T-cells. The same immunological tests were also performed on 10 animals from each group coincident with the kill of the 23 animals remaining after 25 months of exposure (13).

After 13 months of RFR exposure, the exposed experimental animals had a significant increase in both splenic B- and T-cells when compared with the sham-exposed group. This apparent general stimulation of the lymphoid system in the RFR-exposed animals was not detected in the animals evaluated after 25 months of RFR exposure. Comparison of the exposed and sham-exposed rats in the terminal kills did not reveal any significant differences in the percentage or total numbers of B- and T-cells per spleen (Figure 2). The lack of a significant difference in the terminal-kill animals may be the result of age and the onset of immunosenenescence, or it may reflect a random difference at the 13-month period, possibly due to the small number of animals examined.

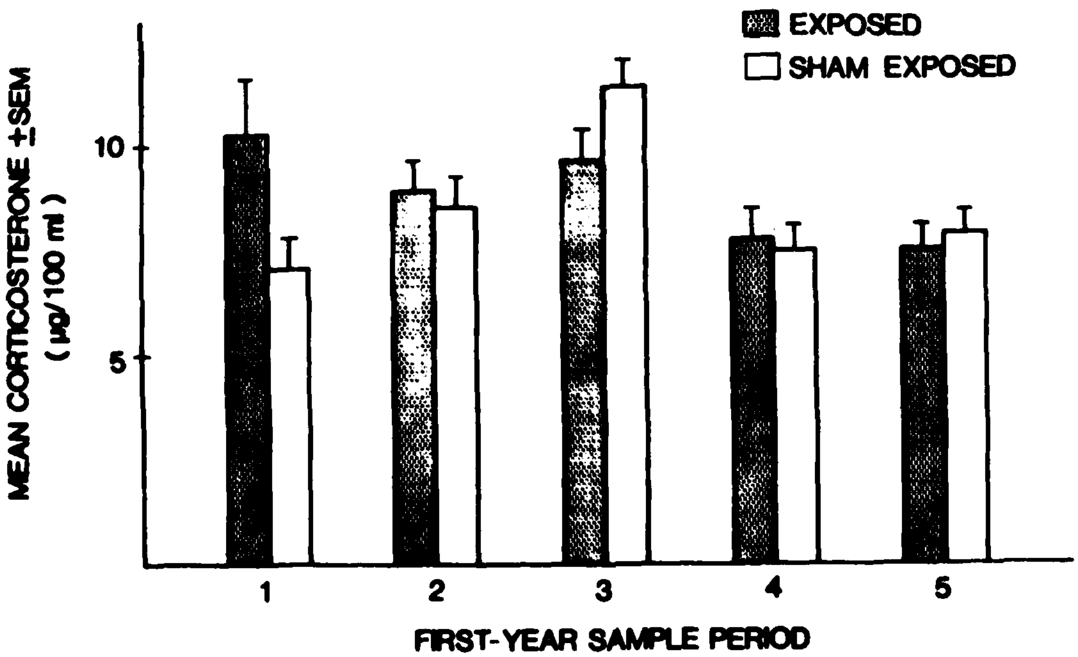
No significant differences were seen between the exposed and sham-exposed rats in the percentage of complement-receptor-positive cells in the spleen at either time of examination, interim or terminal. This procedure indicated no difference between the treatment groups in the maturation of lymphocytes.

The plaque assay performed on animals immunized with sheep red blood cells (SRBC) indicated no statistically significant alteration of the reticuloendothelial system, which first processes the SRBC antigen, and no deficiency in the B-cells' ability to produce antibodies in the presence of T-cells, as the SRBC antigen is T-cell dependent.

The mitogen-stimulation studies after 13 months of exposure revealed a significant difference between groups in their responses to various B- and T-cell specific mitogens. A nonsignificant increase in response to phytohemagglutin (PHA) and a significant increase in response to lipopolysaccharide (LPS) and pokeweed mitogen (PWM) was detected in the RFR-exposed animals. Compared to the sham-exposed animals, the exposed animals also had a significantly increased response to concanavalin (ConA) and a decreased response to purified protein derivative (PPD) (p = .01). Mitogen response data were not available from the 25-month exposure studies because the lymphocyte cultures failed to grow.

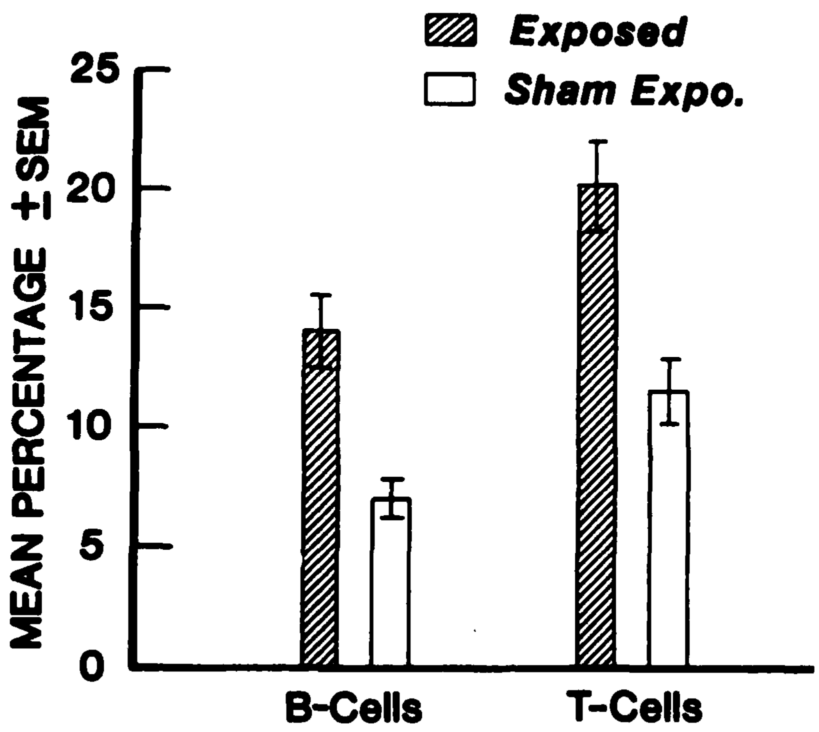


Comparison by treatment group of mean number of moves between quadrants in 14 sessions of open-field testing.

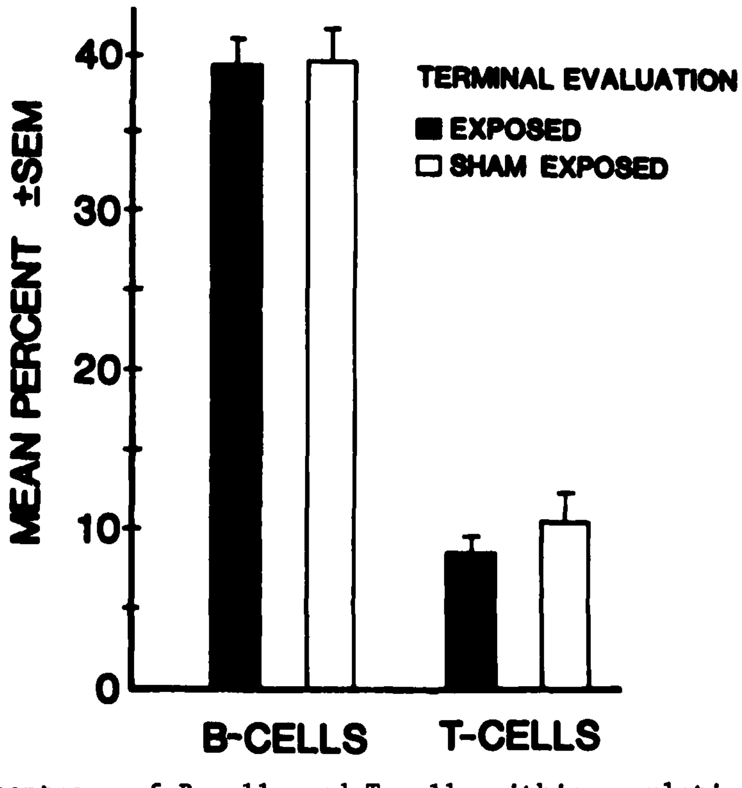


Comparison of mean corticosterone levels from five quarterly determinations during the first year of the project.

FIGURE 1



Mean percentages of B-cells and T-cells within population of splenic lymphocytes for interim-kill exposed and sham-exposed groups.



Mean percentages of B-cells and T-cells within population of splenic lymphocytes for terminal-kill exposed and sham-exposed groups.

FIGURE 2

The equivocal and, in some instances, incomplete nature of these data resulted in a follow-on immunological study being initiated, using a larger number of animals, more precise stimulation assays, and more sophisticated, computer-controlled cell sorting and counting methods. The details of this work are presented later in this report.

Hematology and Serum Chemistry

A rather formidable battery of hematological, biochemical, and hormonal assays were performed, as well as a complete serum protein analysis, at periodic intervals throughout the study. Blood samples were obtained fortnightly during the first year and at 12-week intervals thereafter. The detailed data compilation and analysis together with the materials and methods used can be found in Volume 6 (14) of the Air Force/University of Washington study. The major conclusion that can be reached from the evaluations of the hematology, serum chemistry, protein electrophoretic patterns and fractions, and thyroxine levels is that any significant alterations of these parameters during the lifetime of the exposed animals were to be expected with age and were not due to exposure to pulsed microwave radiation.

The remaining two major categories of endpoints represent the most informative sets of data. Growth and metabolism reflect the organism's expression of its genetic makeup in a closely controlled environment, making the comparison of the exposed versus nonexposed conditions an accurate insight into any expression of cumulative treatment effects. The obverse of this reflection is represented by the data on mortality and cause of death. One can think of it as the subtracting away from the ideal life span, thereby accentuating any cumulative exposure effect that would either accelerate mortality over time, alter the predominant mode of death, or selectively advance the time of appearance of disease entities associated with aging.

Growth and Development

Data for growth and development was gathered by daily measurements of food and water consumption and increase in body weight. In addition, a small subsample of animals were examined at the interim kill, 13 months post exposure, and on termination of the exposure 12 months later. A total-body carcass analysis was done for total moisture, total ash, total crude fat, protein-bound nitrogen and non-protein-bound nitrogen. Total crude fat was further analyzed for specific fatty acid content and for 27 mineral elements. Prior to the carcass analysis, vital organs had been dissected and weighed. From this preponderance of data, only one value showed significant treatment effect, adrenal weight. This isolated finding most likely represents a chance event; as evidence for effects on the adrenal-pituitary axis was lacking, as was any histological finding that would support an effect hypothesis. Growth curves for the two test populations were nearly identical (Figure 3).

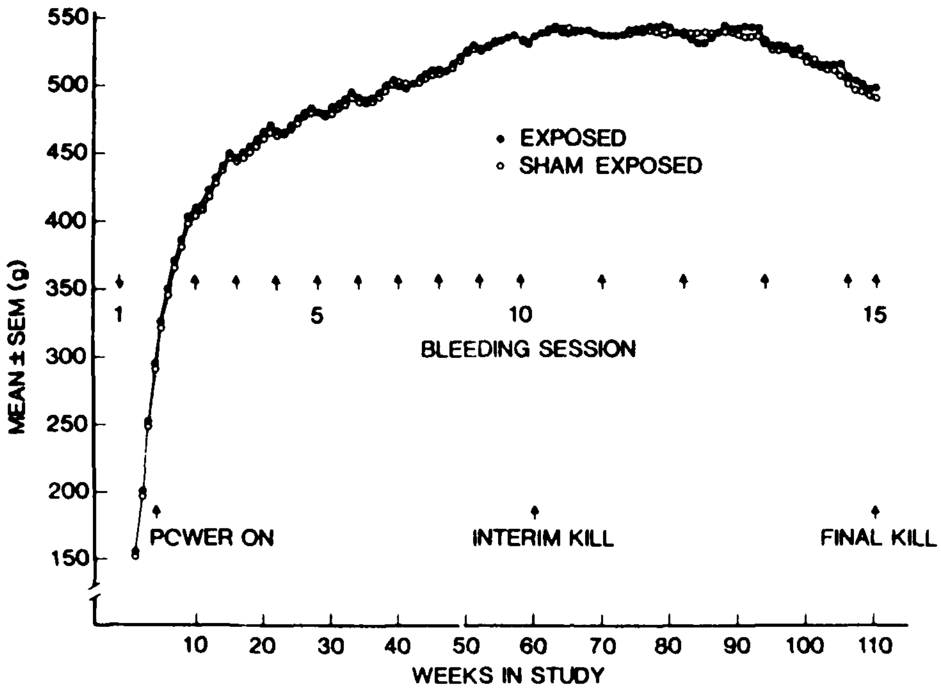


Figure 3. Mean weekly body mass throughout 25-month study. Arrows indicate periodic bleeding sessions as well as other significant events during the course of the study.

The attempt to assess oxygen consumption as a metabolic indicator was less than fully successful. Data from young animals were highly variable and difficult to interpret. For the older animals, the data were more consistent and did not reveal significant treatment differences. Volume 7 of the final report presents the growth and metabolism data in detail (15).

Longevity and Cause of Death

This was the first project to systematically evaluate the histopathology of lifetime exposure to low-level RFR. It was carefully designed to record the onset of lesions, determine their nature, examine their association with natural aging, and detect any differences between control and experimental population in respect to these factors. Much attention was paid to experimental-animal quality control (16). All animals were checked every night to see if any had died or were near death after regular working hours. This helped to limit postmortem autolysis of the tissues. Forty-three rats were killed as part of the interim and terminal evaluations.

One of the overall parameters evaluated was life expectancy. Cumulative survival curves were completed (Figure 4) and the effect of each animal's death plotted. Mean survival time for the exposed animals was 666 days (± SE 15 days); for the sham exposed, 643 days (± SE 18 days). By appropriate statistical tests, no significant effect existed in either early or late mortality.

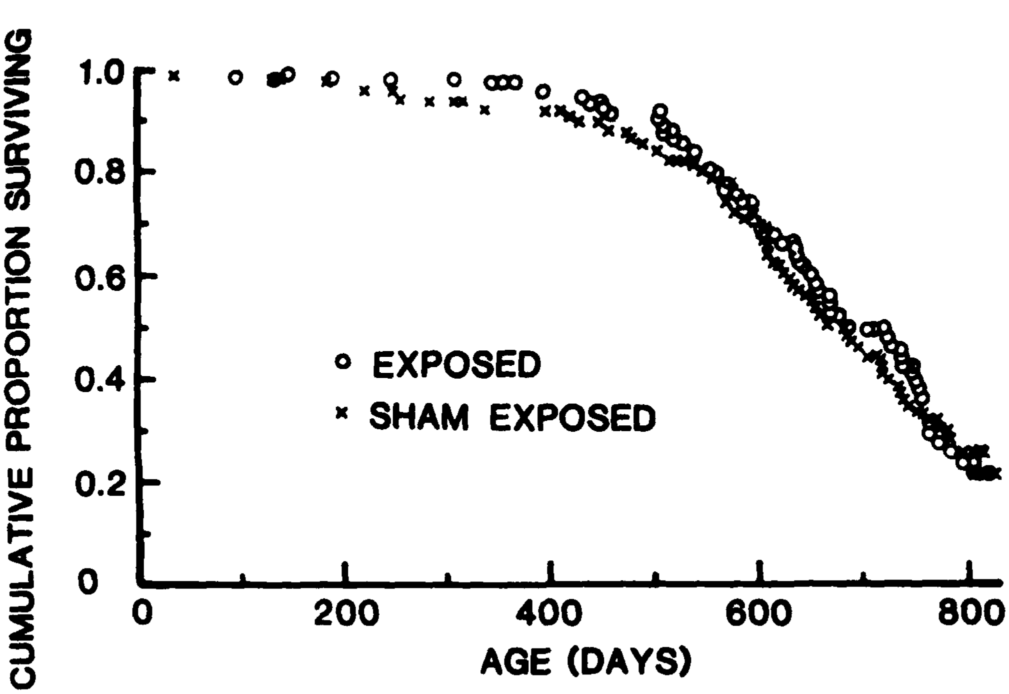


Figure 4. Cumulative survival for both the exposed and sham-exposed animals throughout the course of the 25-month study.

Overall analysis of the major causes of death support the null hypothesis of no association between cause of death and treatment, i.e., exposure. Time of occurrence, early or late, was not different except for an earlier onset of one condition, urinary obstruction, in the sham exposed.

A total of 2,026 non-neoplastic pathological observations were made covering 237 unique combinations of organ and lesion. Neoplastic lesions accounted for 185 observations with 75 unique organ-lesion combinations. Although minor variations in frequency occurred for a few conditions, there was no evidence that specific lesions are more likely in either condition.

The neoplastic lesions were identified as benign or malignant, with the latter further classified as primary or metastatic. The low incidence of neoplasia, with no specific increase in any specific organ or tissue, led to collapsing the data for statistical analysis without regard to area of occurrence. Neither group had an excess of benign lesions when compared to each other or to incidence reported in similar populations of rats. Although the exposed rats had a statistically higher number of primary malignant neoplasms when compared to the sham exposed, the incidence was similar to that reported for untreated rats in other studies under specific-pathogen-free (SPF) conditions. The collapsing of sparse data without regard for tissue origin obscures the true biological activity. It is not generally accepted procedure to collapse tumor data in this manner; if these data were from a study of a suspected carcinogen or toxic agent, the conclusion would be that of no effect. In such studies, one must see either a statistically significant increase in a

particular type of tumor normally present or any incidence of tumors not usually seen in the species in question. Neither of these criteria were met in the RFR study.

One swallow does not a summer make, and one study, no matter how comprehensive, does not delineate all the factors in long-term low-level RFR exposure. In this study, for example, clear-cut results were not obtained from the small-sample screening for immunological effects. To this end, the immunological portion is being repeated with twice the number of animals (40); more precise assay techniques, and computer-aided, sophisticated cell-sorting and counting equipment. Similarly, additional metabolic data for younger animals are being generated, including ambient temperature effects, seeking to establish an effect threshold.

Some criticism was leveled during the inception of the study, challenging the concept of frequency scaling. To address this issue, the Engineering Experiment Station at the Georgia Institute of Technology (GIT) was contracted to design, construct, and operate a multianimal exposure facility in the 425-450-MHz region (25,26). The facility is now being used to study the effects of prolonged exposure to 435- MHz RFR. Experiments are currently underway to evaluate the response of cardiovascular dynamics to exposure, using rats with chronic aortic catheter implants (27).

Until solid epidemiological data is available, some concern for long-term effects will remain. The difficulty in assessing implied very subtle effects without a distinguishing lesion or disease entity will continue to fertilize the blossoming of anecdotal epidemiology data. In the meantime, rational review of the existing data provides no reason to predict adverse consequences from lifespan exposure to currently allowable levels of RFR.

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The second approach to estimating errors in the NSAR measurements is presented in section 2 of the table. It is to compare our measurements with accurate calculations for test objects or with other determinations of human whole-body RF absorption rates. The comparison to Tell et al. is based on assuming that the grounded SAR is proportional to the square of the current to ground, which both we and Tell measured.

The last section of the table presents an overall estimate of the likely error in our NSAR determinations. That estimate is a judgement based on all the information presented in Table 1. With the exception of the one higher frequency, most of the systematic errors tend to cancel when comparisons are made between measurements. The precision in comparisons is about 5-10% of the larger figure.

TABLE 1. SUMMARY OF DOSIMETRIC ERROR ESTIMATES

Method of estimation [Reference]		Percent error in NSAR	
		10-25 MHz	40.68 MHz
1. <u>List Separate Error Estimates</u>			
(a) Est. systematic measurement errors in power (4 sources) and fields (2 sources) [15].	rms:	16	16
	max:	36	36
(b) Dielectric loading effect on absorbed power [15]		< 12	–[a]
(c) Exposure field errors due to subject - cell interactions:			
(i) reflections from cell end walls [8]		< 10	<10
(ii) finite length of subject compared to septum-wall separation [10].		~ 0±4	10±5[b]
(iii) incompletely suppressed resonances [18].		~ 0	±20
2. <u>SAR Data Comparisons</u>		[(Meas.-Ref)/Ref]X100%	
(a) Meas <u>vs</u> calc. for thin cylinders [19].		3±10	-
(b) Meas <u>vs</u> Guy & Chou's result[c] [8, 12].	grounded:	55±?	-
	free space:	-4±?	-
(c) Meas <u>vs</u> Tell's meas.[d] [13, 14]:	grounded:	-7±20	-
3. <u>Overall Estimate</u>		±25	±45

[a]Not tested.
[b]A correction of 10% has been applied to the NSAR data.
[c]Their data at 3 MHz scaled $\propto f^2$ to 10 MHz.
[d]Assuming SAR(grounded) $\propto$ [current through feet]^2.

In the original version of the TEM cell, interactions between the human body and some of the resonances of the higher-order transverse electric modes were found to cause significant changes in the effective exposure fields above 25 MHz [17]. Suppression of the resonances by cutting the cell walls longitudinally was found to reduce the resonance interactions to the extent that dosimetry could also be done at 40.68 MHz (an Industrial, Scientific, and Medical frequency) and at 26 MHz (but only in free space) [18].

All volunteers were adult males in good health. The experimental protocol was approved by the human experimentation committees of both our organization and the National Research Council. Exposures were limited to 1 h per day at a power density that was typically 10 $\mu W/cm^2$ and in no case more than 20 $\mu W/cm^2$. No one ever absorbed at a rate exceeding 1 W. The exposures caused no apparent effects in any of the subjects. (The longest cumulative exposure has been 100 h spread over 2 years.) Most of the results were obtained from five different volunteers.

Absorption Measurements

The power absorbed by the empty TEM cell is determined from computer-averaging the incident, reflected, and transmitted power to and from the cell. The absorption of the subject is determined from the average changes in the three power readings when the subject is positioned in the cell [15].

The dosimetry results will be expressed in terms of the normalized specific absorption rate (NSAR), defined as the ratio of specific absorption rate (SAR, W/kg) to exposure power density (W/m^2).

While the basic SI units of NSAR are $W \cdot kg^{-1}/W \cdot m^{-2}$, we will employ the practical units of $mW \cdot kg^{-1}/mW \cdot cm^{-2}$.

Dosimetric Accuracy

The accuracy of our NSAR determinations has been estimated, using various approaches, in several different reports [8, 10, 13, 15, 18, 19]. The methods and results are summarized in Table 1.

Section 1(a) of the table summarizes the estimated measurement errors that are not affected by the differences between TEM-cell exposures and free-space exposures. The remainder of the first section specifically deals with errors attributable to the difference in exposures, i.e., errors due to the interaction between the subject and the TEM-cell field patterns. The dielectric loading effect is defined as a change in the cell's own absorption rate resulting from the presence of a subject inside the cell. The fact that the subject fills half the space between septum and wall (3.64 m) was found to cause negligible error in exposures at frequencies below 25 MHz, but an error of 10 $\pm$ 5% at 40.68 MHz, near the grounded resonance. The cell's incompletely suppressed TE_{mnp} resonances also caused exposure errors at 40.68 MHz.

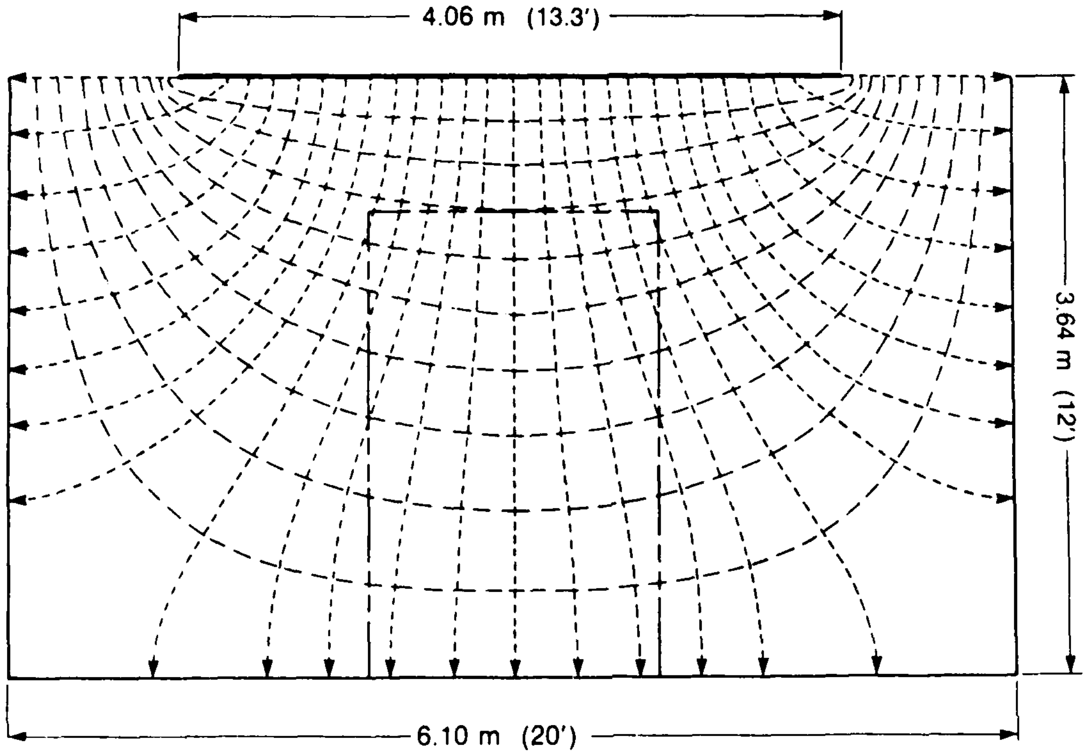

Figure 1. Electrostatic calculation of the field pattern in a transverse plane of the TEM cell. Only half the cell is shown.

Legend: ________ inner and outer conductors; -------- electric field lines; __ __ __ electrostatic equipotential lines (pattern similar to the RF H-field lines); __ _ __ outlines the cell volume occupied by subjects in the free-space and grounded conditions.

INTRODUCTION

Current radiofrequency radiation (RFR) safety standards [1-3] are based in part on presumed rates of human whole-body RF absorption [2-5]. The rates used in setting the standards were determined only from theoretical calculations (reviewed by Durney [6]) and measurements on saline-filled or tissue-equivalent models (reviewed by Gandhi [7]). Our research group has been the only one that has had the opportunity of directly measuring whole-body RF absorption rates in human volunteers. We have just recently reported the results of four different studies of human RF absorption rates over the frequency range from 3 to 41 MHz [8-11]. Another group, by an indirect method that was used only for frequencies up to 3 MHz, has also determined whole-body absorption rates using human volunteers [12].

We have also determined the local absorption rate in the region of the ankles by measuring the current through the feet of a grounded subject [13]. Tell et al. [14] performed similar experiments using a different exposure system.

The purpose of this paper is to summarize the experimental results on human RF-absorption rates that are relevant to RFR protection, and to apply those findings to current RFR safety standards. No new data is presented in this report. Some of the most important results have been reproduced as Figures 1-6. Other findings have been summarized or reexpressed in Figure 7 and Tables 1-3. Thus, this report is intended to be a useful summary for people who are involved in setting or using RFR safety standards but who do not work full time in this field.

METHODS

Exposures

The volunteers are exposed inside a very large (6.1 x 7.3 x 13.0 m) TEM cell. The calculated electromagnetic exposure field pattern is shown in Figure 1. The measured pattern agrees very well with the calculated one [15]. The figure shows that in the region of the cell occupied by the subjects, the field pattern is a good approximation to a plane wave. The cell is large enough to permit simulation of plane-wave exposures in all body orientations under both free-space and grounded conditions.

The orientation of the subject's body with respect to the simulated plane wave is denoted by the usual ellipsoid-equivalent notation [16: pp. 11-13]: in the "ABC" orientation the field vector A (A = E or K or H) is aligned with the body length, B with the side-to-side direction, and C with the front-to-back direction. In this system, six principal body orientations are possible: EKH, EHK, KEH, KHE, HEK, HKE. The EKH and EHK orientations will sometimes be referred to together as the E orientations; and the K and H orientations, similarly.

APPLICATION OF HUMAN WHOLE-BODY RF ABSORPTION MEASUREMENTS TO RFR SAFETY STANDARDS

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SUMMARY

Human whole-body RF absorption rates have been measured as a function of body orientation, wave impedance, separation from ground, and frequency (from 3 to 40 MHz). Results applicable to RF radiation protection are summarized. The worst-case practical exposure situation is taken to be the far-field whole-body exposure of a man wearing footwear and standing on a ground plane. Assuming that 0.4 W/kg is a safe whole-body specific absorption rate (SAR), the permitted exposure levels (PELs) set by the 1982 ANSI standard are well supported by our results. On the other hand, the PELs set by NATO STANAG 2345 are unsafe at most frequencies from 5 to 40 MHz. RF currents through the feet of grounded subjects were also measured. For the maximum exposures permitted by the ANSI standard, the RF currents cause a localized SAR in the ankle region of 16 W/kg.

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In the entire overexposed groups, serum enzyme levels, blood counts, blood pressures, sedimentation rates, and electrocardiograms were all unremarkable to clinical review, suggesting the absence of clearly defined tissue damage.

Clinical symptomatology reported by patients seen soon after exposure often included such complaints as headache and nausea. These symptoms can be interpreted as an anxiety response to the exposure, but an organic basis cannot be ruled out completely.

More formal statistical analysis of the medical record data is currently underway. This analysis is evaluating the rate and kind of medical symptoms and signs as a function of radiation dose and frequency and body part exposed.

PRELIMINARY CONCLUSIONS

Review and analysis of these Air Force RFR accident files will continue. Additional information will be forthcoming. At this time, the following conclusions are evident:

(1) Of the 296 suspected overexposures, only 58 (~20%) were confirmed; the other 80% were within the PEL.

(2) About half of the overexposures were detected because the individual(s) felt a warming sensation.

(3) Essentially all of the overexposures were partial-body exposures.

(4) Actual exposure times were most often less than 6 minutes.

(5) Most of these exposures occurred at frequencies between 1 and 10 GHz.

ACKNOWLEDGMENT

Special appreciation is extended to TSgt Anita Neuhaus, Radiation Biology Branch, Radiation Sciences Division, U.S. Air Force School of Aerospace Medicine, for her diligent efforts to extract and summarize the physical data from the RFR accident repository. I am also indebted to Dr. Richard A. Albanese, Data Sciences Division, of the U. S. Air Force School of Aerospace Medicine, for his review and analysis of the case files and preparation of the Medical Findings section of the paper.

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TABLE 5

ACCIDENTAL RFR EXPOSURES WITHIN THE PEL* AS A FUNCTION OF AVERAGE POWER DENSITY

Number of Cases	Power Density Range (mW/cm^2)
95	0 - 1
57	1 - 14
20	15 - 39
23	40 - 100
1	101 - 250
1	251 - 1,000
2	Unknown

*PEL = 3600 $mW \cdot s/cm^2$ in any 6-min period.

TABLE 6

ACCIDENTAL RFR EXPOSURES WITHIN THE PEL* AS A FUNCTION OF EXPOSURE TIME

Number of Cases	Exposure Time Range
29	0 - 1 s
39	1 - 11 s
36	15 - 60 s
29	1 - 6 min
45	8 - 60 min
14	2 - 100 h
3	101 - 500 h
4	Unknown

*PEL = 3600 $mW \cdot s/cm^2$ in any 6-min period.

CLINICAL IMPRESSIONS

Medical review of the physical examinations following RFR overexposure revealed few consistent clinical patterns. Even when intense local exposure occurred and was perceived, erythema and/or edema were rare findings at the time of physical examination. Lenticular findings such as vacuoles and opacities were noted in some overexposed individuals receiving radiation to the head. None of these findings, however, were deemed clinically significant since there was no concomitant visual impairment. Also, it has not been possible to reliably determine whether these findings were present prior to the radiation event. The ocular findings noted are commonly encountered on routine ophthalmologic examination (3,4).

Abnormalities on detailed psychological tests were occasionally found. Again, however, preradiation baselines are not available for comparison or interpretation. Also, no abnormalities were noted on neurological examinations done along with the psychological studies.

TABLE 2

CONFIRMED OVEREXPOSURES AS A FUNCTION OF AVERAGE POWER DENSITY

Number of Cases	Power Density Range (mW/cm^2)
9	15 - 30
16	40 - 100
14	120 - 250
13	350 - 1,000
3	1,000 - 3,000
1	16,000 - 100,000
1	100,000 - 160,000
1	Unknown

TABLE 3

CONFIRMED OVEREXPOSURES AS A FUNCTION OF EXPOSURE TIME

Number of Cases	Exposure Time Range
7	1 - 10 s
11	15 - 60 s
18	1 - 6 min
21	8 - 60 min
1	Unknown

TABLE 4

ACCIDENTAL RFR EXPOSURES WITHIN THE PEL* AS A FUNCTION OF FREQUENCY

Number of Cases	Frequency Range
2	1 - 10 MHz
3	20 - 90 MHz
14	0.1 - 0.9 GHz
61	1.0 - 6.0 GHz
30	8 - 10 GHz
3	10 - 14 GHz
20	15 - 35 GHz
66	Unknown

*PEL = 3600 $mW \cdot s/cm^2$ in any 6-min period.

the investigation of each alleged overexposure, make the appropriate RFR measurements, and prepare the official report. Often this approach has not been satisfactory. About 80% of the Air Force investigations in the continental United States are now conducted by specially trained personnel assigned to the Air Force Occupational and Environmental Health Laboratory at Brooks Air Force Base, Texas. The actual radiation measurements are made with the accident victim(s) present, if possible, so that exact conditions of the exposure can be duplicated. Care is taken to ensure that the measurement instrumentation (usually a hand-held/portable monitor such as the NARDA Broadband Isotropic Monitor) is calibrated and that the individual(s) making the RFR measurements and others present are not exposed to levels in excess of the PELs. A complete report is prepared to document each accident investigation, and the data are entered in the Air Force RFR accident repository.

SUMMARY OF FINDINGS

The medical data from accidental RFR exposures are incomplete in many respects due to lack of standardization of clinical examinations, but these accident files can provide important anecdotal evidence concerning human exposure to RFR fields. Of the 296 cases of suspected overexposures in the Air Force RFR accident repository, only 58 (20%) were confirmed to have exceeded the 10-mW/cm^2 (3600 mW·sec/cm^2 in any 6-min period) PEL. Of the 58 confirmed overexposures, 26 persons clearly felt a warming sensation as the first indication of the RFR exposure, 20 did not feel the RFR, and 12 cases were inconclusive. Thus 45% of those persons overexposed felt the RFR and terminated the exposure. Of the 238 alleged cases of overexposure that were later confirmed as not exceeding the PEL, 26 persons (11%) felt a warming sensation and terminated the exposure before exceeding the PEL, 173 persons did not feel the RFR, and 39 cases were inconclusive. Tables 1-6 summarize the accidental RFR exposures as a function of frequency, average power density, and exposure time. For the confirmed overexposures, most were in the frequency range between 1.5 and 10 GHz and the exposure times were generally less than 6 minutes. The average power densities cover a wide range, as seen from Table 3. For the suspected overexposures that were later confirmed to be within the PEL, most were in the frequency range between 1 and 10 GHz; the same as the confirmed overexposures. Likewise, most of the exposure times were less than 6 minutes, but the average power densities were considerably lower, as would be expected.

TABLE 1

CONFIRMED OVEREXPOSURES AS A FUNCTION OF FREQUENCY

Number of Cases	Frequency Range
1	20 MHz
7	200 - 500 MHz
18	1.5 - 6 GHz
24	8.0 - 10 GHz
5	15 - 35 GHz
3	Unknown

INTRODUCTION

Occupational safety and health is given a high priority in the U.S. Air Force. Program responsibilities are carefully defined in a series of USAF directives, and procedures to control exposure to RFR are documented in Air Force Occupational Safety and Health (AFOSH) Standard 161-9 (1). This standard tells how to prevent harmful exposures to RFR and what actions are required when an accident happens and/or when a suspected overexposure has occurred. By the authority of this standard, personnel are trained and assigned responsibilities to maintain a high level of safety in all Air Force RFR operations. The Air Force operates a large number of RFR emitters, however, and accidental overexposures have occurred (2). In the past 10 years the Air Force has investigated more than 300 RFR accidents, of which 58 were confirmed overexposures.

RFR ACCIDENT INVESTIGATIONS

Every suspected exposure to RFR in excess of the permissible exposure limit (PEL) is thoroughly investigated (1). Whenever a suspected overexposure to RFR occurs, the individual(s) involved is required to report the accident to his or her supervisor. The supervisor must see that the accident victim(s) is taken to the emergency medical facility. If the patient is not in obvious danger, the symptoms of any possible injury or illness requiring diagnostic evaluation or treatment will determine whether or not hospital admission is required. Air Force workers potentially exposed to RFR are subject to illnesses and injuries typical of all industrial workers. Lifesaving support measures, based upon clinical symptoms being exhibited by a patient, must be given highest priority. Most individuals overexposed to RFR at intensities below those that cause frank burns, will manifest little or no immediate evidence of altered physiological functions or symptoms of distress. The primary concern is to quantitate the exposure history in relation to existing symptoms and to document medical baselines against which to measure changes, should they occur. A comprehensive case record is essential to determine the need for follow-up medical examinations and to evaluate subsequent exams.

Whenever an alleged overexposure to RFR occurs, the Director of Base Medical Services initiates an investigation and insures that its results are documented. The investigating officer, often the base Bioenvironmental Engineer (BEE), gathers the following background information on the alleged incident: (1) name, rank, and service number, (2) RFR emitter nomenclature and operating parameters at the time of the incident (radiation frequency, peak and average power, gain and scan characteristics of the antenna, beam configuration and size, and duty cycle), (3) description of what happened including date, place, time, and duration of the exposure, and the individual's positions in relation to the emitter.

After the medical and RFR emitter evaluations are completed, the accident is reconstructed as accurately as possible to determine the likely RFR exposures to the individual(s) involved. Originally the local BEE would conduct

HUMAN EXPOSURES TO RADIOFREQUENCY RADIATION (RFR)
A REVIEW OF RFR ACCIDENTS

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WHOLE-BODY ABSORPTION RATES

Whole-body RF absorption rates were studied from 3 to 41 MHz. The effects of body orientation, frequency, separation from ground, two-body interactions, and wave impedance were all studied. In general, the dependence of the NSAR on those factors was about as predicted theoretically. The one major difference was in the magnitude of the NSAR figures, which were as much as four times larger than the predicted values. The findings for the effect of each physical factor will be briefly described below and then summarized in a table.

Effect of Body Orientation, Frequency, and Grounding

The effect of body orientation and frequency on the absorption rate of one subject exposed in free space is illustrated in Figure 2. Since the E orientations are seen to absorb at a much higher rate than the K and H orientations, the latter are considered relatively unimportant for RFR protection in the 10-40-MHz frequency range. E-polarization absorption rates for five subjects at two frequencies are presented in Table 2.

TABLE 2. REPRESENTATIVE NSAR MESUREMENTS FOR FIVE HUMAN SUBJECTS EXPOSED IN AN EKH ORIENTATION UNDER BOTH FREE-SPACE (FS) AND GROUNDED (G) CONDITIONS

Subject	Mass	Height	Whole-body NSAR ($mW\cdot kg^{-1}/mW\cdot cm^{-2}$)			
			40.68 MHz		10 MHz	
	(kg)	(cm)	G	FS	G	FS
F	85	175	-	-	52.5	8.8
G	55	170	-	-	76.6	7.4
I	78	178	558	159	65.7	7.6
L	70	172	585	147	68.0	6.6
M	71	171	624	165	57.3	8.1
Average	72	173	589	157	64.0	7.7

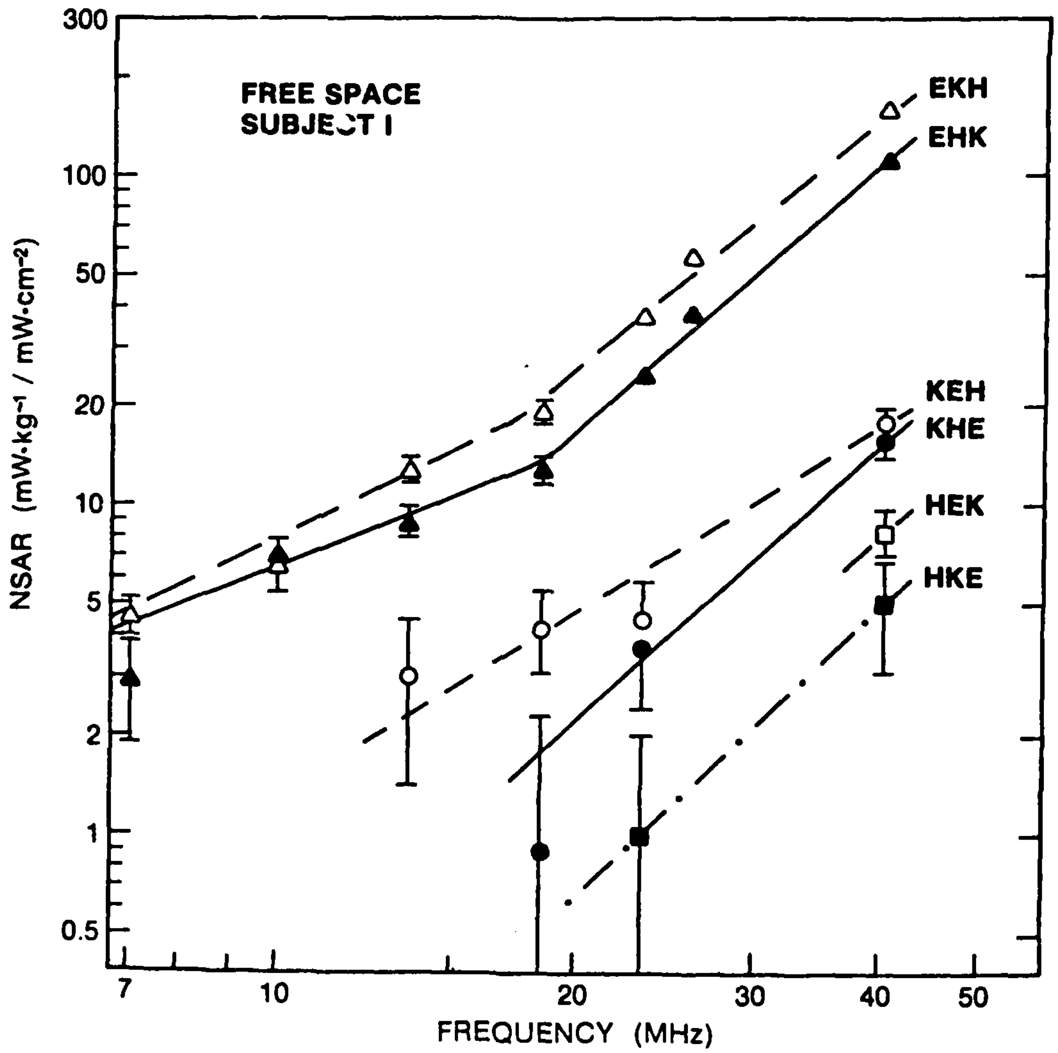

Figure 2. Frequency dependence of the whole-body absorption rates for subject I in free space. Six different body orientations are labeled with the ellipsoid-equivalent notation defined in the text. Data points are mean $\pm$ SE(N). N varies from 6 (at NSAR = 100) to 16 (at NSAR = 1).

As seen in Table 2, the average mass and height of the volunteers are close to the values (70 kg and 175 cm) usually assumed for a standard man. The NSAR values vary between subjects by 10-45%. The E-polarization absorption rates, averaged for the same five subjects, are shown as a function of frequency in Figure 3. The observed change in frequency dependence of the free-space curves at 20 MHz is consistent with both measurements and calculations for models filled with saline or tissue-equivalent material.

The maximum NSAR for a grounded subject should occur when the length of the subject is approximately equal to a quarter wavelength. The measurements indicate that this occurs at 40 ±5 MHz. The peak of the absorption-rate curve cannot be located more precisely due to experimental difficulties at frequencies above 25 MHz. Below the grounded resonance, the NSAR curves for a grounded subject followed a frequency dependence very close to f^2.

For frequencies below 10 MHz, we combined our grounded current measurements [13] with the results of several other workers [12, 14, 20] and show that the f^2 law is followed very closely all the way from 60 Hz to 10 MHz.

The effect of changing the body configuration while keeping the trunk in an E orientation was also studied [11]. The results are presented in Table 3 which also summarizes the effects of the other factors.

Raising the arms over the head doubles the absorption rate, likely because the effective length of the body has been extended. For the same reason, moving to a sitting position from a standing position halves the absorption rate.

TABLE 3. EFFECT ON THE WHOLE-BODY ABSORPTION RATE OF CHANGES IN THE EXPOSURE SITUATION

Line #	Exposure Situation: standard except as noted.	NSAR[a] (% of result for standard situation)			
		Grounded		Free space	
		10-25 MHz	41 MHz	10-25 MHz	41 MHz
1.	<u>Standard situation</u> single exposures; bare feet; EKH orientation; arms at sides; E/H = 377 ohms	≡100	≡100	≡100	≡100
2.	EHK orientation	90	95	70	75
3.	K orientations	–	–	15	10
4.	H orientations	–	–	5	5
5.	Arms over head, HE	175	135	200	180
6.	"Sit at chair" (legs bent)	45	–	55	–
7.	Separation from : 5mm gap	45	90	–	–
8.	Ground plane (air gap):20mm gap	25	70	–	–
9.	Footwear (socks and shoes) used	≤55	≤85	100	100
10.	Two-body interactions	≤100	≤100	≤250	≤250
11.	Wave impedance: $\eta = 2.0$	200	200	185	185
12.	$\eta \equiv (E/377H)$: $\eta = 0.5$	50	50	65	65

[a] Results are typically ±5-10% of the standard result. For the wave-impedance effect, NSAR ≡ SAR/(E.H).

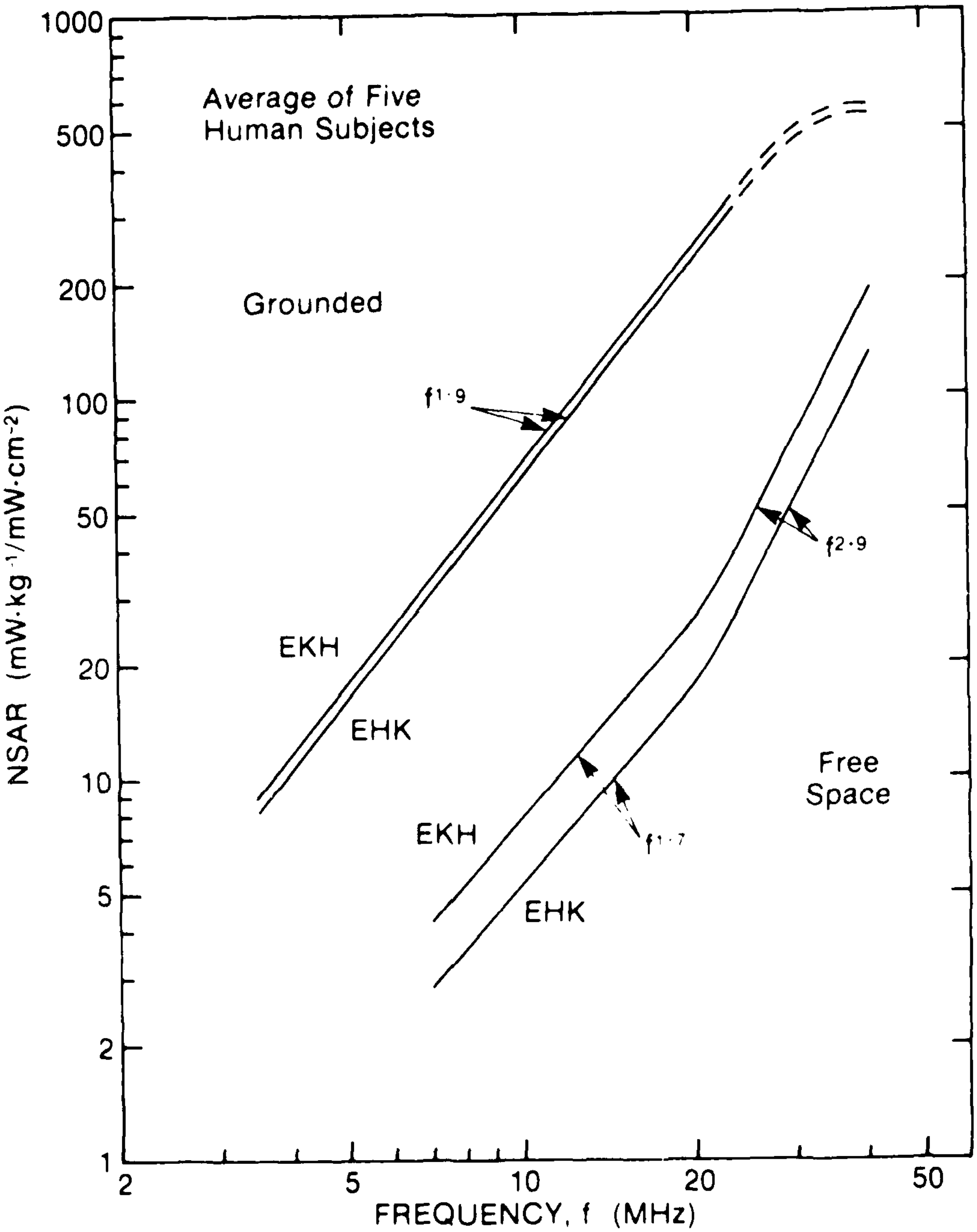

Figure 3. Frequency dependence of the average absorption rates for five human subjects in both the EKH and EHK orientations under both free-space and grounded conditions. The dashed portion of the grounded curve indicates that there are no measured points between 25 and 40 MHz. The last point is at 40.68 MHz.

Effect of Separation from Ground

The effect of an air gap between the feet and the ground plane is shown in Figure 4. At below-resonance frequencies, the effect of a 5-mm air gap is quite dramatic--a 55% reduction in NSAR. The same separation at the grounded-resonance frequency causes only a 10% reduction in absorption rate.

In practical exposure situations, the feet are usually separated from any ground plane by footwear (shoes and socks). The effect of footwear on the absorption rates is seen in Figure 5. The two combinations of footwear used for that experiment represent the maximum range of results found in testing five combinations of footwear at one frequency. Results are very similar to all below-resonance frequencies. At 40.68 MHz, however, footwear produces a much smaller reduction in absorption rate, which is consistent with the data of Figure 4 for the effect of an air gap.

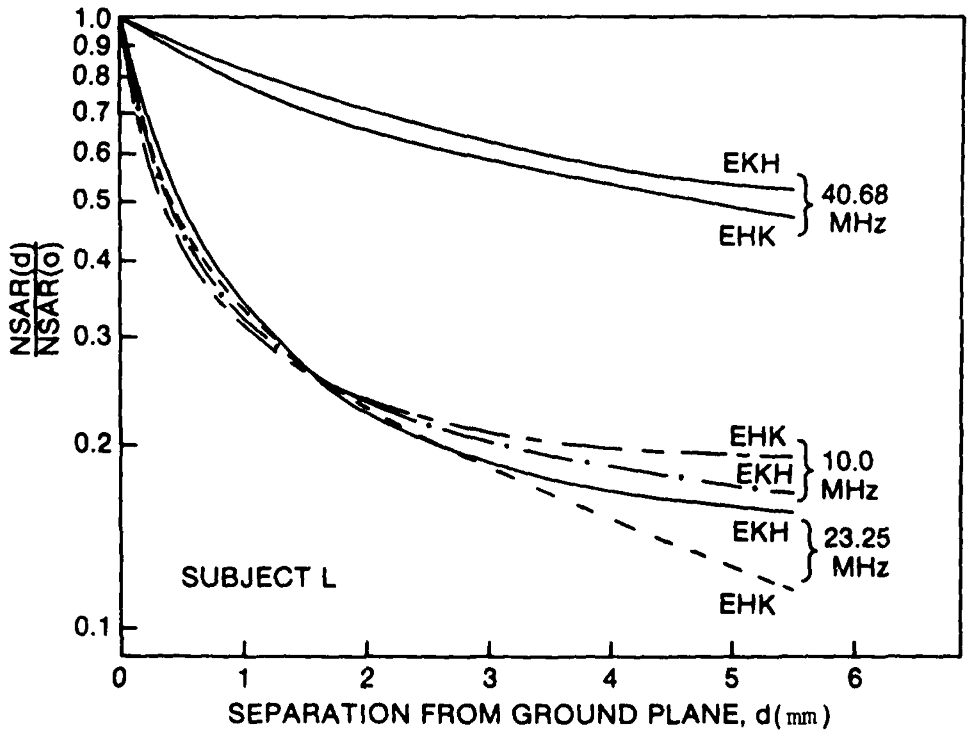

Figure 4. Dependence of the whole-body absorption rate on the separation between a subject's feet and the ground plane. The effect of frequency and body orientation (EKH or EHK) is also shown.

In occupational exposure situations, where the grounding effect may occur, it is recommended that footwear always be worn. This will provide some radiation protection at all frequencies: a reduction in RF absorption rate of 15-35% near-resonance and 45-75% at below-resonance frequencies. For the commonly used ISM frequency of 27.12 MHz, the reduction is estimated from Figure 5 to be between 40 and 60%. A second radiation protection alternative is the use of a thick rug, rubber mat, plastic sheet, or any other insulating material over the ground plane.

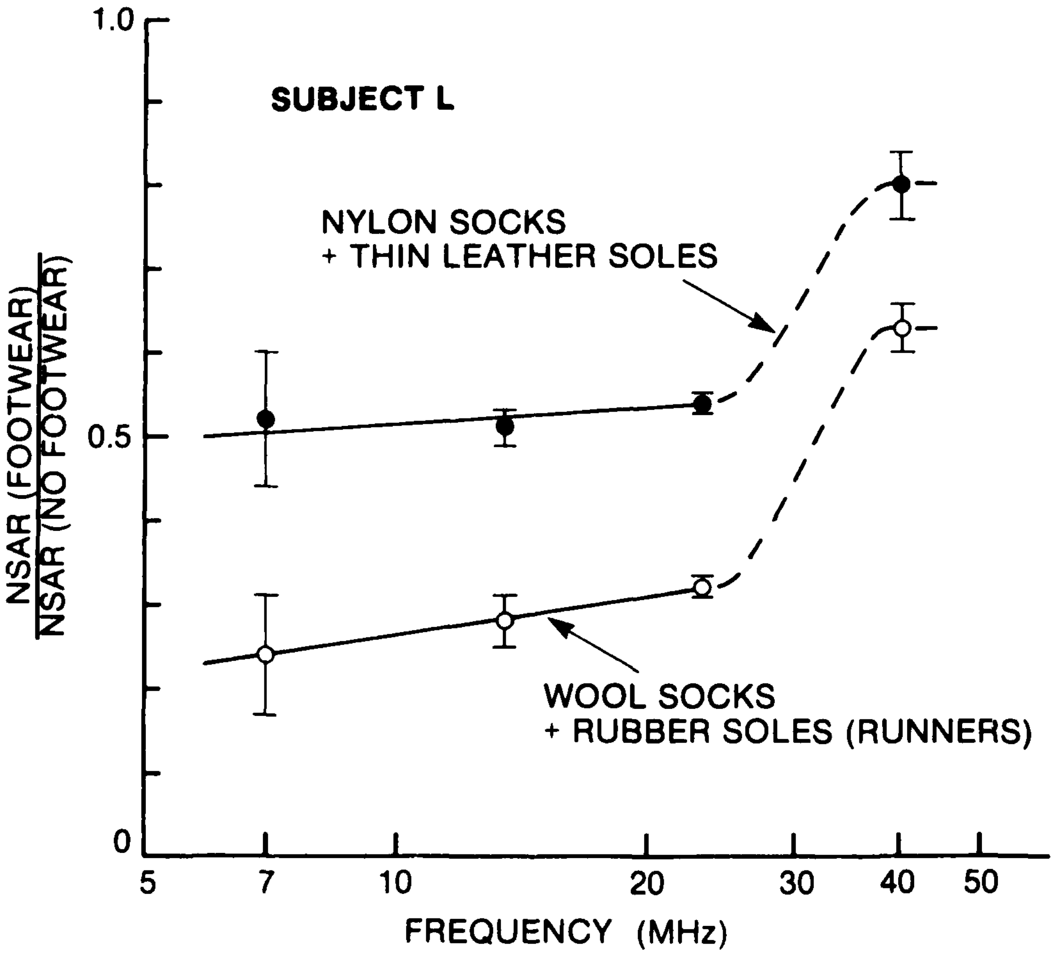

Figure 5. Frequency dependence of the reduction in absorption rate caused by two combinations of footwear. The measurement frequencies are 7.0, 13.56, 23.25, and 40.68 MHz.

Two-Body Interactions

To a limited extent, we could expose two subjects inside the cell at spacings comparable to a fraction of a wavelength. The subjects could be separated by only half a wavelength at the highest frequency (40.68 MHz), and that much separation could be achieved only in the K direction. The same general result was found for body separations in both the K and H directions; the interaction effect decreased the total absorption rate for the grounded case and increased it for the free-space case. The largest interaction effect, illustrated in Figure 6, was for a free-space separation of half a wavelength in the K direction. There is no simple way of determining how the total absorption rate is distributed between the two people.

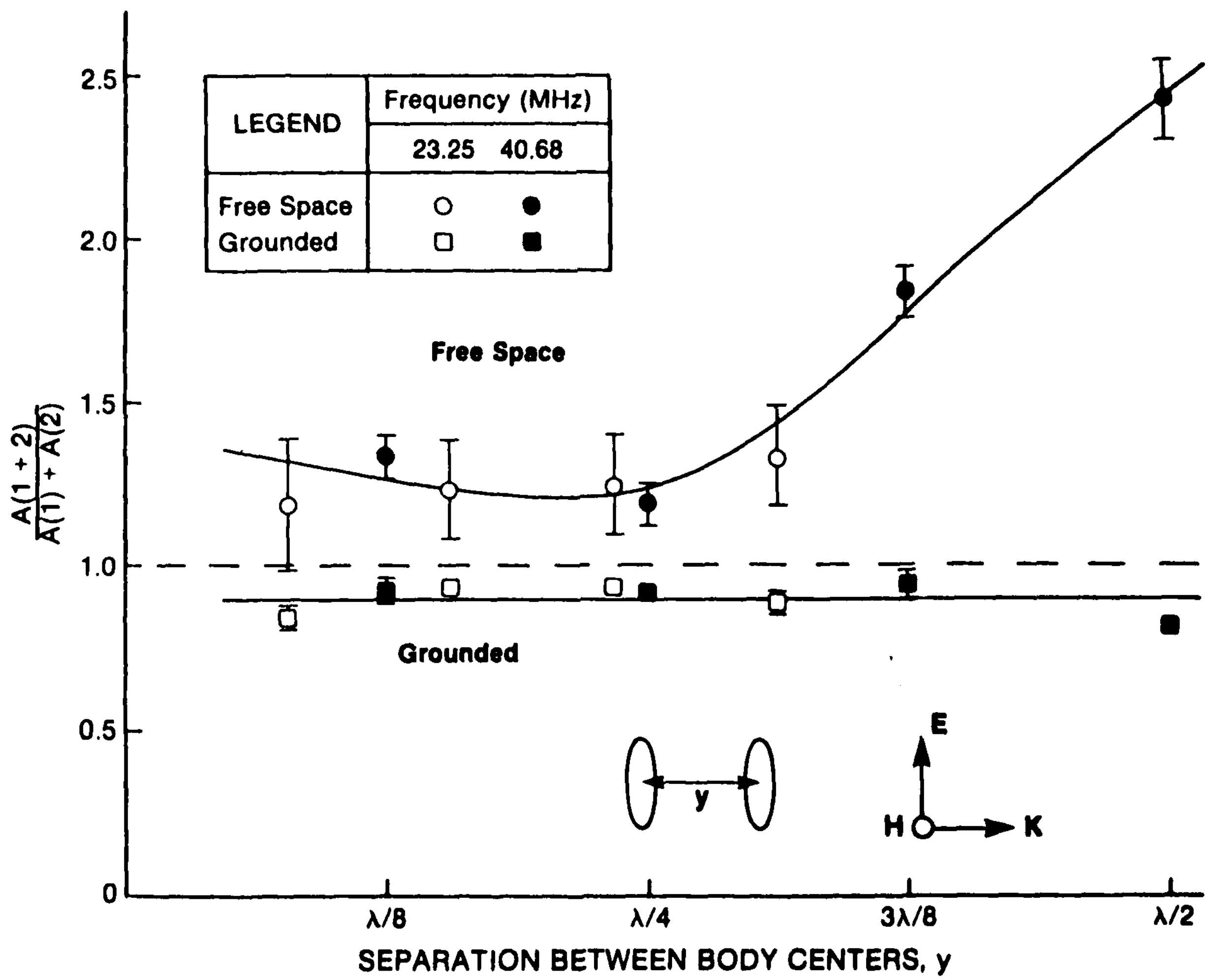

Figure 6. Interaction effect for two bodies, in E polarization, separated in the direction of propagation of the wave. The ordinate is the ratio of the absorption rate of the two subjects exposed together, to the sum of their separate absorption rates. Subjects L and M were used. Data points (mean ±SE) are based on six measurements for the free-space case and four for the grounded case. Smooth curves have been drawn through the middle of the data points.

Even with the maximum interaction effect, the free-space NSAR is still 17% less than the grounded rate for singly exposed subjects. Thus the two-body interaction effects, although they occur, are not important for radiation protection in the 20-40-MHz range. The data suggest, however, that people exposed at the free-space resonance frequency (about 70 MHz) may absorb at a greater rate in free space than when grounded-- as a result of the two-body interaction effect.

Wave Impedance Effect

The wave impedance is defined as the ratio of the electric field (E) to the magnetic field (H), in a given exposure situation. In the far field of an antenna that ratio is 377 ohms. Thus the normalized wave impedance, defined as $\eta = (E/377H)$, is unity for far-field exposures. One aspect of near-field exposures which could be simulated with our apparatus was values of η different from unity.

The method is restricted to values of η within the range (0.5, 2.0). Although this range is limited, it does include some of the most important near-field exposure situations. For example, Durney et al. [16; Fig. 38] calculated that $0.7 \leq \eta \leq 1.8$ for separations of at least 0.1λ from an electrically short dipole operating from 10 to 50 MHz. Rogers [20: Fig. 1] also calculated that $0.5 \leq \eta \leq 2.0$ for separations of more than 5 m from an 11-m (35-foot) naval ship antenna operating in the lower HF band (2 to 20 MHz).

RF absorption rates were measured for the E orientations and different values of η. The fraction of the absorption rate attributable to each of the electric and magnetic fields was then determined by a graphical technique. Results were the same for both E orientations. For free-space exposures at frequencies from 13.56 to 40.68 MHz, about 90% of the RF absorption rate was attributable to the electric field. For grounded exposures at frequencies from 7.0 to 40.68 MHz, nearly 100% of the absorption rate resulted from the electric field exposure. These conclusions are expressed in terms of changes in the NSAR in Table 3. They should not be extended to frequencies outside the range given, nor to normalized wave impedance values outside the range (0.5, 2.0).

For near-field exposures to HF-band radiation, the electric field is by far the most important of the two exposure fields. Thus when the higher measured exposure field near an antenna is the magnetic field, some relaxation of the exposure limits may be permitted by a RADHAZ officer, after careful consideration. The modified exposure limits would likely be frequency dependent. In situations where space is at a premium, such as near naval HF-band fan or whip antennas, an investigation of this radiation-protection option would appear worthwhile.

RF CURRENTS TO GROUND

Current Measurements

RF currents through the feet of grounded human subjects were measured from 0.5 to 10.0 MHz [13]. The current to ground was found to be directly proportional to both frequency and electric field, with an average constant of proportionality of $A = 344 \pm 14(4)\ \mu A/(V \cdot m^{-1} \cdot MHz)$. Other workers have found that $A = 275\ \mu A/(V \cdot m^{-1} \cdot MHz)$ for frequencies from 60 Hz to 200 kHz [12, 19] and that $A = 300$ to $350\ \mu A/(V \cdot m^{-1} \cdot MHz)$ from 0.7 to 1.5 MHz [14]. This remarkable constancy of A over five orders of magnitude in frequency is the basic fact underlying the f^2 absorption law for grounded subjects over the same frequency range.

Ankle Absorption Rates

It is generally agreed [19, 21] that for a human standing on a ground plane, the highest localized absorption rates occur in the ankles, where all of the ground current passes through the smallest area of cross-section. From the measured ankle size and RF current, and assuming an average tissue conductivity of 0.44 S/m (2/3 of the wet-tissue value [16]), the ankle dosimetry data presented in Table 4 were compiled. The importance of these results will be discussed in another section.

TABLE 4. ANKLE DOSIMETRY DATA FOR A GROUNDED BAREFOOT MAN EXPOSED TO RF RADIATION

Subject	Area of cross-section (1 ankle) (cm^2)	Ankle data for ANSI exposure[a]			NSAR ($mW \cdot kg^{-1}/mW \cdot cm^{-2}$)	
		I (A)[b]	J (mA/cm^2)	SAR (W/kg)	Ankle	Whole-body
D	42	0.73	8.7	17	1800	-
G	29	0.60	10.3	24	2500	77
L	37	0.66	8.9	18	1900	68
M	60	0.64	5.3	6	600	57
Average	42	0.66	8.3	16	1700	67

[a] Calculated figures for the subject's ankles if he were exposed to 190 V/m ($9\ mW/cm^2$), the maximum exposure permitted for 10 MHz by ANSI standard C95.1-1982.

[b] Total RF current through both ankles.

APPLICATION OF DOSIMETRIC RESULTS TO STANDARDS

Whole-Body Absorption Rates

The following conclusions are drawn regarding exposure standards based on whole-body absorption rates from 3 to 41 MHz. The absorption rate is greatest for the EKH body orientation with the subject's feet in direct contact with the ground plane. The normalized SAR is maximal at 40 $\pm$5 MHz, which is the frequency for the resonance condition of a grounded man. Below resonance, the absorption rate is proportional to f^2 for all frequencies from 60 Hz to 25 MHz. The use of footwear reduces the grounded absorption rate by about 50% at below-resonance frequencies and 20% at near-resonance frequencies.

In assessing the worst-case exposure situation, two-body interactions will be ignored because they do not cause enhanced absorption for the grounded case and they are unlikely to occur, at least for very long, in any practical exposure situation. The worst-case exposure condition, based on our results, is for a person standing with bare feet in contact with an ideal ground plane and with the whole body exposed to a far-field radiation pattern. This combination of circumstances is unlikely to occur in practice because footwear is usually worn, the ground plane is usually not ideal, and exposures are often part-body and/or in the near field of the antenna. Since we have data on the effect of footwear, and its effect is likely less than the effect of the other factors, a conservative approach to RFR safety would be to take into account only the effect of footwear on the whole-body absorption rates. Thus for calculating an exposure standard, we will take the realistic worst case to be a far-field whole-body exposure of a grounded man wearing socks and shoes.

To convert the NSAR data to a frequency-dependent permitted exposure level (PEL), we will take 0.4 W/kg to be a safe specific absorption rate for continuous whole-body absorption of RFR. The ANSI committee [2] drew that conclusion after a careful analysis of the available data, and also noted that 0.4 W/kg is 10% of the threshold for harmful effects of RFR due to acute exposures (less than 1 hour). Using data from the uppermost curves of Figures 3 and 5, the PEL corresponding to an SAR of 0.4 W/kg was calculated for the case of a man wearing footwear and standing on a ground plane. The resulting curve is shown as (d) in Figure 7, where it is compared to three other occupational safety standards.

As may be seen in Figure 7, the PEL curve set by the ANSI standard [2] is very close to the curve we calculated; i.e., the ANSI standard, from 3 to 40 MHz, is completely supported by our results.

The PELs set by NATO STANAG 2345 [1] are seen in Figure 7 to be too large at most frequencies above 5 MHz. For example, a man exposed to the NATO PELs could absorb 2.1 W/kg at 9.9 MHz and 4.4 W/kg at 40 MHz. These figures correspond, for a 70-kg man, to a whole-body absorption rate of 150 to 300 W. Considering that the basal metabolic rate is 100 W and that 4 W/kg is the threshold for harmful effects from acute exposures, the absorption rates that could result from exposure to the NATO PELs are unsafe. In other words, the PELs set by the NATO standard are unsafe at most frequencies from 5 to over 100 MHz. This conclusion would not change much if the standard were based on

0.4 W/kg for a man exposed to RF in E polarization in free space. The PEL curve previously calculated for that case [8: Fig. 5] lies below 2 mW/cm^2 from 40 to over 100 MHz.

The third standard that we compare our results to in Figure 7 is the interim guideline recently published by IRPA [3]. Above 10 MHz, it also is based on limiting the SAR to 0.4 W/kg. Below 10 MHz, it is designed to prevent RF burns or shocks when a human makes contact with ungrounded metallic objects exposed to RFR. This hazard undoubtedly exists, but its importance in practical exposure situations has not yet been established. Furthermore, the

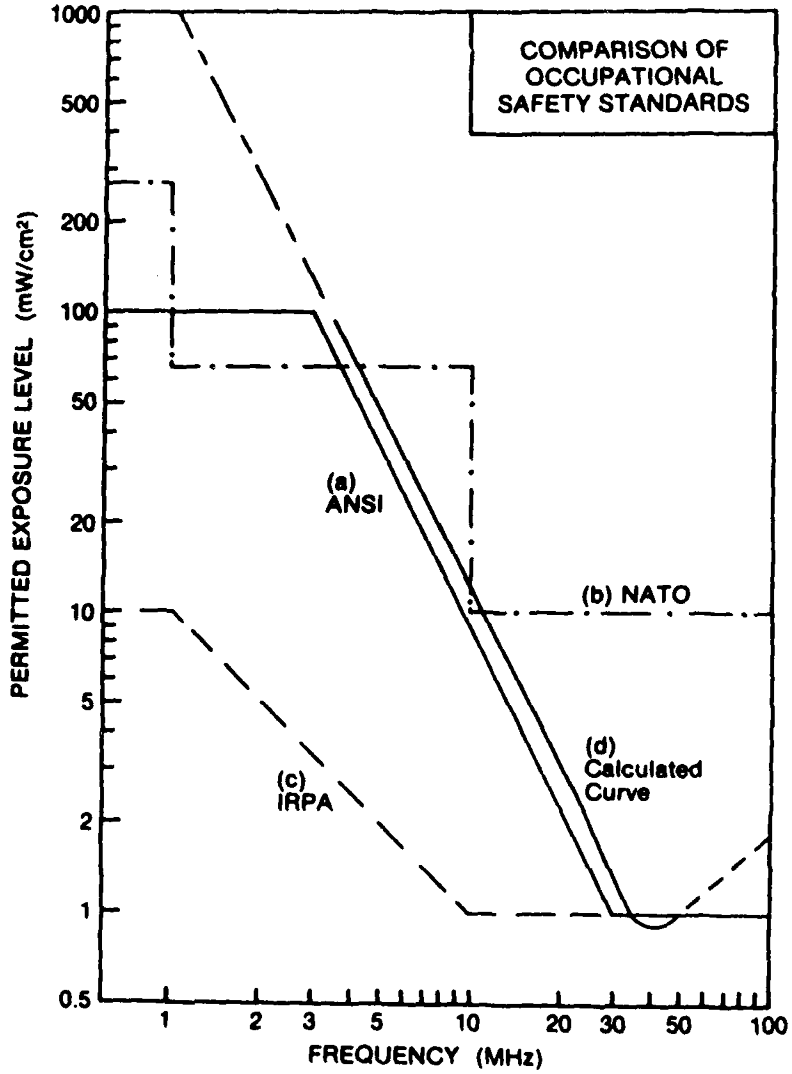

Figure 7. Comparison of three occupational exposure standards with one based on our results. (a) ANSI standard C95.1-1982; (b) NATO STANAG 2345; (c) IRPA's 1984 interim guidelines; (d) PEL for an SAR of 0.4 W/kg, based on our measurements for a man with footwear, standing on a ground plane.

IRPA guideline is based on only two calculations for that problem, only one of which has been peer reviewed. For these two reasons, the IRPA standard below 10 MHz is considered too premature to be supported at this time. The use of a larger PEL at the lower frequencies, a feature of all three standards, is, of course, supported by our conclusions.

Ankle Dosimetry

About 0.67 A of RF current passes through the ankles of a grounded man exposed to RFR at the PEL of the ANSI standard. The RF current is about the same from 3 to 40 MHz. While the effect of this relatively large RF current likely will not be directly sensed, it does produce a large localized heating in the ankle region. For the case of a barefoot man standing on a ground plane, the ankle SAR figures (in Table 4) range from 6 to 24 W/kg, with an average of 16 W/kg. The use of footwear reduces the squared current through the feet, and hence the ankle SAR, by at least a factor of 3 [13: Fig. 3]. On the other hand, this reduction is apt to be cancelled by the undoubtedly nonuniform SAR distribution within the ankles. Thus for a man exposed to the ANSI-standard PEL, the SAR in 1 g of ankle tissue would likely be about 24 W/kg for some individuals and 16 W/kg for the average person. These figures significantly exceed the local SAR limit of 8 W/kg set by the ANSI standard. Nevertheless, the local SAR limit should probably not apply to regions of the body containing no vital organs; i.e., the arms and legs. This viewpoint is implicit in the Canadian standard [23: section 2.4], which permits twice as much exposure of the extremities as the rest of the body. Even taking this into account, the maximum ankle SAR for exposures under the ANSI standard is a cause for concern. More study of this problem, using models, is recommended. Also, all RFR standards-setting bodies need to clarify their positions regarding the permitted peak local SAR values, and whether or not the same limit applies to vital organs as to other parts of the body.

Special Exposure Situations

Some of our experimental results may be used to assess special exposure situations that are of great practical importance but of limited generality. One example would be the exposure of sailors to large magnetic fields near naval HF-band antennas, where it might be possible to relax the permitted exposure levels. Other applications are suggested by the data found in Table 3. The PEL could be increased for exposures where the subjects are sitting, but it should be reduced for grounded people working with their arms over their heads. Finally, in situations where people are effectively exposed in a grounded condition, a significant degree of RFR protection would result from the use of footwear and insulating floor mats.

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II. SPECIAL TOPICS

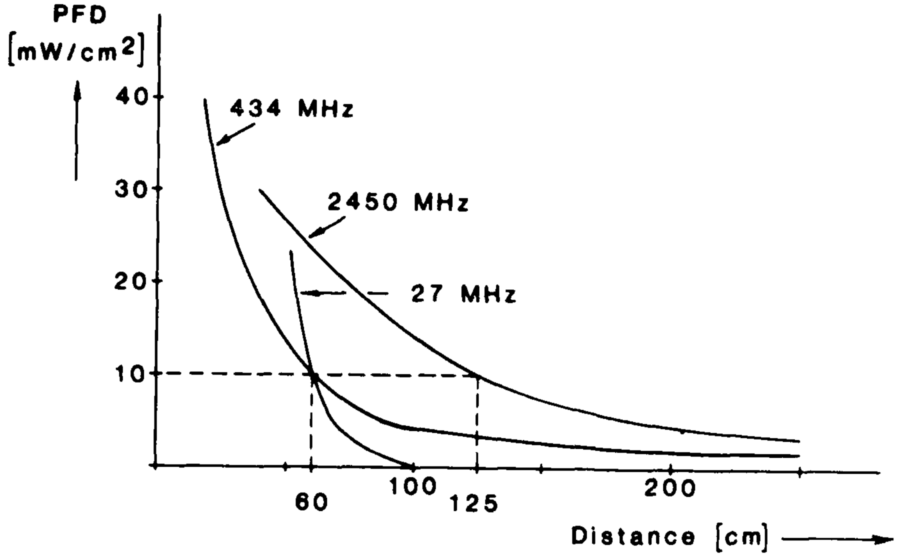


Figure 13. Maximum radiation levels in front of three diathermy units.

Type	2450MHz	434MHz	27MHz
Measured Values	62 (≙100%)	57 (≙100%)	147 (≙100%)

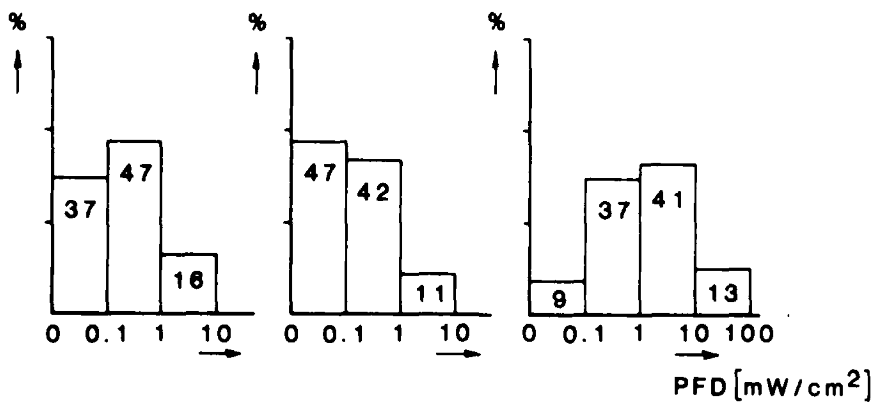


Figure 14. Histograms of exposure levels.

The conclusion that can be drawn from these measurements is that, with the chosen power settings, all values were smaller than 10 mW/cm^2 except for some treatments with the 27-MHz unit. Measurements at places in the close vicinity of the applicator and treated body parts have been excluded in these histograms; at those places the PFD was much higher (max. 1500 mW/cm^2). Although results found in the literature are often difficult to compare because of different local circumstances, power settings, etc., the order of magnitude is the same.

A definite PFD-level can now be selected, and a computer program interconnects points of this chosen level. The result is an ISO-PFD contour. Figure 12 illustrates an example of these ISO-PFD contours in front of a 434-MHz diathermy unit equipped with a long-field emitter. From these contours it is no longer possible to extract information about the height of the maximum PFD that was present. The power applied to the applicators has been set to the maximum allowable power specified for that kind of applicator.

The maximum PFD that occurs in a vertical plane in front of an applicator versus the distance of that plane to the applicator is illustrated in Figure 13. The curves represent the maximum envelopes for all the applicators used.

From these measurements the conclusion can be drawn that in the worst case the PFD is reduced to less than 10 mW/cm^2 at a distance of 125 cm in front of the microwave unit, and at half this distance for the other two units.

The second part of this section concerns the measurements carried out during different treatments. These treatments formed part of the training for physiotherapists and were carried out at four training centers. During these treatments the PFD was measured at a number of positions, close to the units and close to the patients. The power settings during the treatments were such that the patients experienced a light sensation of heat (Mitis). The results of these measurements are collected in Figure 14. The 27-MHz histogram has been constructed from the maximum C- or H-value at each point.

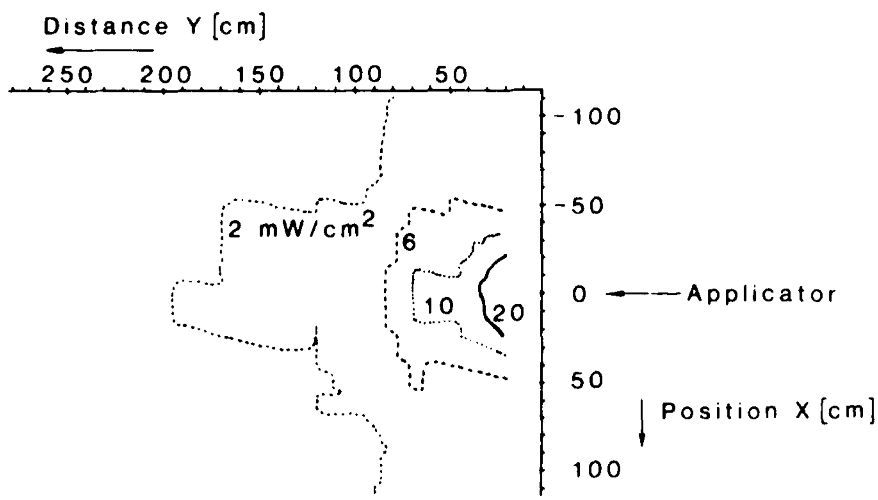


Figure 12. ISO-PFD contours in front of 434-MHz unit (longitudinal-field director).

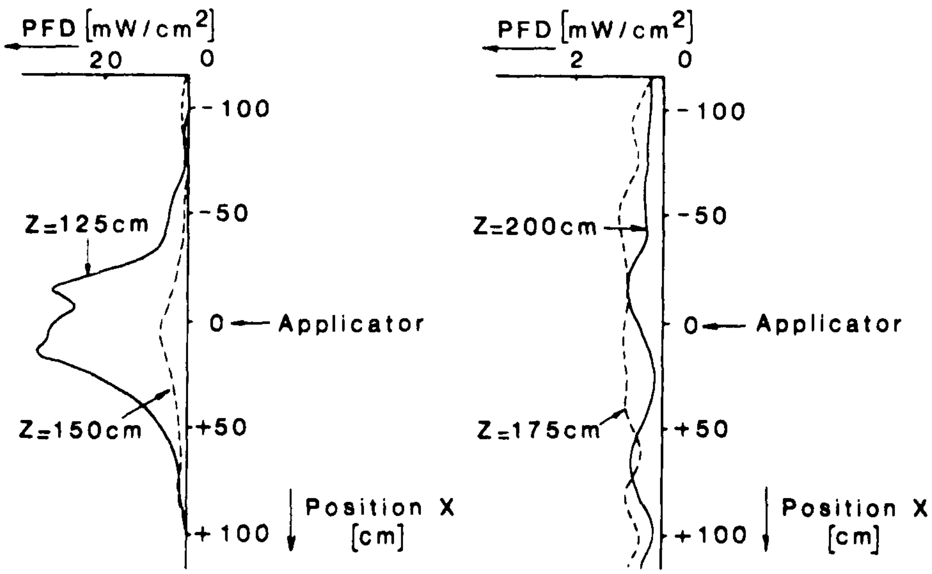


Figure 10. PFD at a distance of 19 cm in front of a 434-MHz unit for several heights.

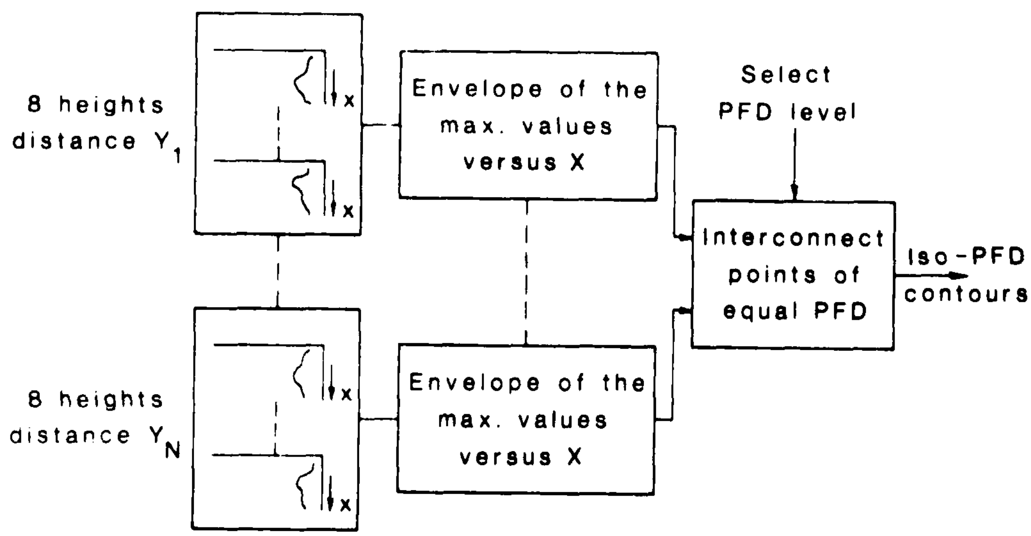


Figure 11. Mapping procedure.

The distance between the probe and the applicator in the horizontal Y-direction and the height of the probe above the ground plane (Z-direction) have to be set manually. In the horizontal X-direction the probe is moved electrically. A signal whose amplitude is proportional to the position of the probe is supplied to the X-axis of an X-Y recorder, while the output of the probe (thus the field intensity) is supplied to the Y-axis of the recorder. Series of horizontal scans were made in the X-Z plane at a definite distance Y from the applicator. Figure 9 is a photograph of the measuring setup at the laboratory.

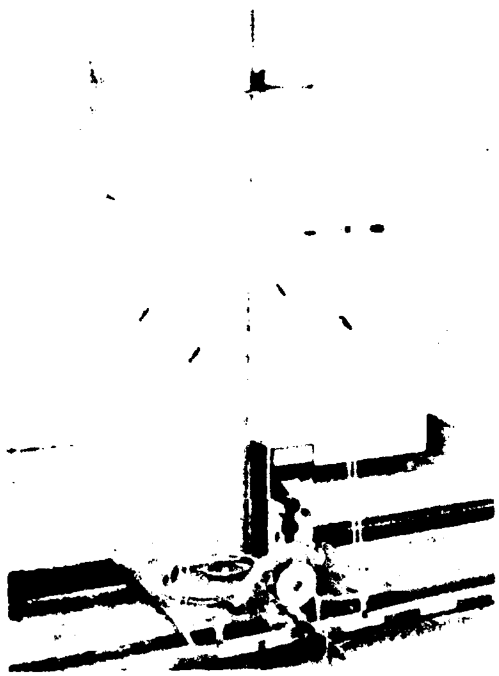


Figure 9. Measuring setup at the laboratory.

Results of these horizontal scans are shown in Figure 10. Here the measured PFD versus the position X in front of a diathermy unit at four different heights has been plotted. In fact, measurements are made at eight different heights and at various (N) distances.

To get an impression of the spatial distribution of the PFD, data reduction is needed. The way in which this reduction took place is illustrated in Figure 11. From each set of eight plots taken at a certain distance, an envelope of the maximum values versus the position X can be constructed. The total number of plots is now reduced to N.

Diathermy Equipment

Measurements carried out in the vicinity of diathermy equipment are divided into two parts:

- measurements made at the laboratory;
- measurements made during real treatments.

Table 2 lists the number and types of units involved as well as the number of different applicators.

A schematic outline of the measuring setup used for the measurements at the laboratory is shown in Figure 8. The probe can be moved on its mechanical positioner in all three directions in front of the diathermy unit.

TABLE 2. RF DIATHERMY EQUIPMENT

	Type	No. Units	No. Applicators
At the laboratory :	27 MHz	1	4
	434 MHz	1	3
	2450 MHz	1	4
During 30 treatments :	27 MHz	5	5
	434 MHz	2	3
	2450 MHz	4	3

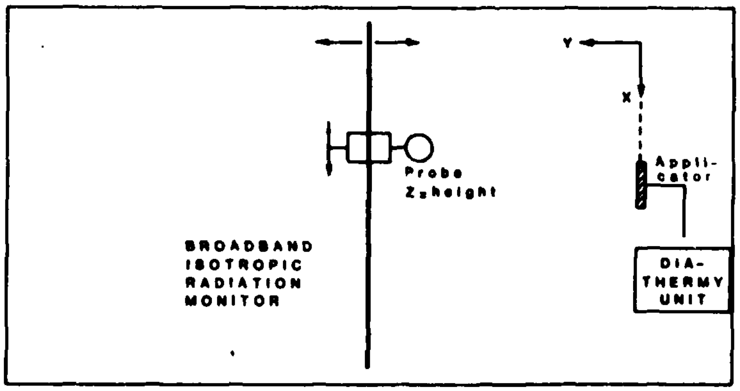


Figure 8. Top view of the measuring setup at the laboratory.

Type	Sewing	Shuttle Tray	Turntable
Measured Values	12 (≙100%)	32 (≙100%)	40 (≙100%)

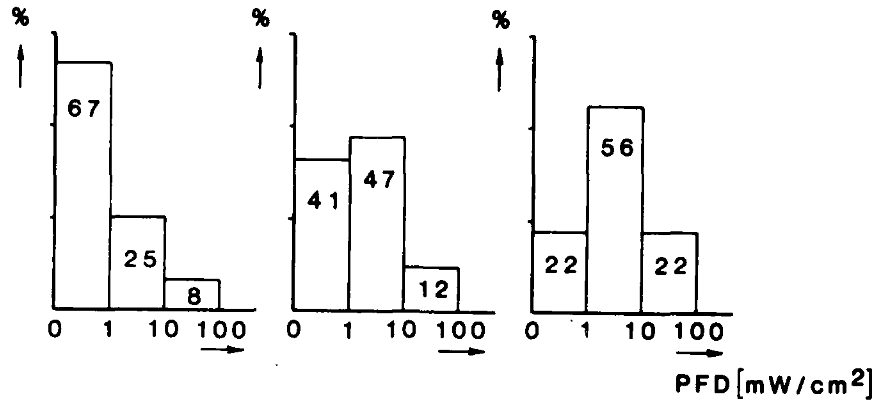


Figure 7. Histograms of exposure levels (corrected for duty cycle).

From the measured PFDs the following conclusions might be drawn:

- the exposure levels are fairly high;
- peak levels are even 2-10 times higher, depending on the duty cycle; the maximum measured peak level was 300 mW/cm^2;
- shielding can be very effective to reduce these levels; a shielding effectiveness of more than 20 dB has been measured;
- the sample of sealers is too small to state that the results are applicable to all types of sealers.

TABLE 1. EXTREME EXPOSURE LEVELS (CORRECTED FOR DUTY CYCLE)

Sealer type	No. units	Exposure level (mW/cm^2)		Part of body max. exposed
		min	max	
Sewing	3	<0.2	26.4	Knees
Shuttle Tray	5	0.2	30	Head
Turn-table	5	0.2	29.7	Waist

RF Seal Machines

Concerning the RF seal machines, 13 devices (namely 3 sewing types, 5 shuttle-tray types, and 5 turntable types) were measured at two plants. The operating frequency was 27 MHz, while the output power of the devices varied between 0.1 and 10 kW. An example of a shuttle-tray RF sealer is shown in Figure 6.

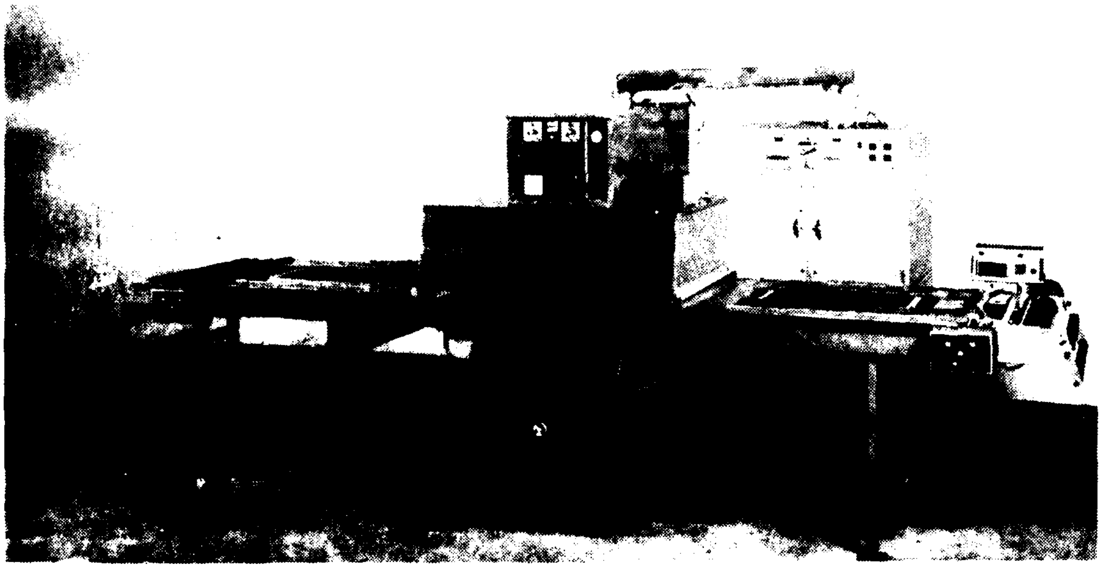


Figure 6. Example of shuttle-tray sealer.

Typical operation involves arranging the material to be processed on a tray and moving it manually or automatically to the applicator. The models most frequently encountered have two trays. Two persons, standing on the left and right side with respect to the applicator, operate the machine. Field intensities were measured in the vicinity of the operator positioned in the normal operating position.

A summary of the results is given in Figure 7. Roughly speaking, about 14% of all the values are higher than 10 mW/cm^2; 57% are higher than 1 mW/cm^2. In the vicinity of the turntable machine, 78% of the values are above 1 mW/cm^2. All these values are corrected for the duty cycle. The duty cycle is defined as the ratio of the time period when the RF power is "on" to the duration of a typical operational cycle (i.e., the sum of the time period when the power is "on" and "off").

Table 1 lists the extreme exposure levels for the various types of sealers. The levels are almost the same, but the part of the body exposed to the maximum level is different.

MEASUREMENTS

Field strength measurements have been made in the vicinity of RF seal machines and RF diathermy equipment. Many of these measurements were carried out close to the devices (close in terms of wavelength).

In this environment (near field) the electromagnetic components have different characteristics than in the far field, and the energy coupling to a worker is complex and depends on many factors. Despite this, the measurements of C- and H-fields have been translated to an equivalent planewave power density in most cases. This has been done only for reasons of comparison with current proposed safety standards which, for the time being, do not differentiate between these different conditions. The figures given later should be considered as such.

The following instruments were used during the surveys:

1. E-field survey meter, Narda, model 8616, probe 8621:

   dynamic range : 0.2 - 20 mW/cm^2
   frequency : 300 MHz - 36 GHz
   calibration accuracy: ± 0.5 dB
   spatial response : isotropic

2. E-field survey meter, Narda, model 8616, probe 8644:

   dynamic range : 20 mW/cm^2 - 2 W/cm^2
   frequency : 10 - 3000 MHz
   calibration accuracy: ± 0.5 dB
   spatial response : isotropic

3. E-field survey meter, Instruments for Industry, model EFS-2:

   dynamic range : 3 - 300 V/m
   frequency : 10 kHz - 220 MHz
   calibration accuracy: ± 5% of full scale
   spatial response : unidirectional

4. H-field survey meter, Narda, model 8616, probe 8631:

   dynamic range : 0.2 - 20 mW/cm^2
   frequency : 10 - 300 MHz
   calibration accuracy: ± 0.5 dB
   spatial response : isotropic

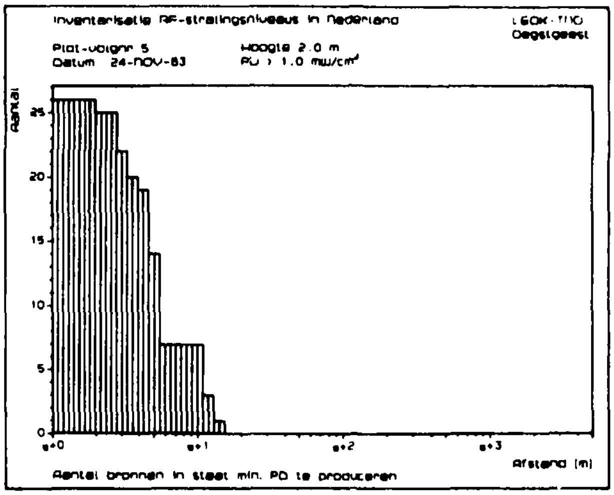


Figure 4. Plot of number and distances of transmitters capable of producing a selected PFD.

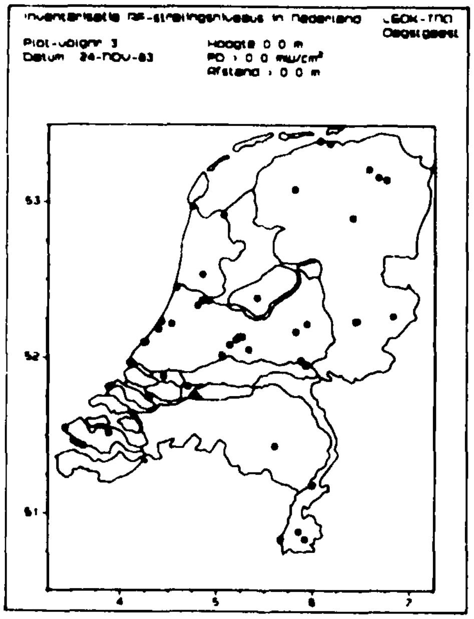


Figure 5. Map of the locations of subset transmitters.

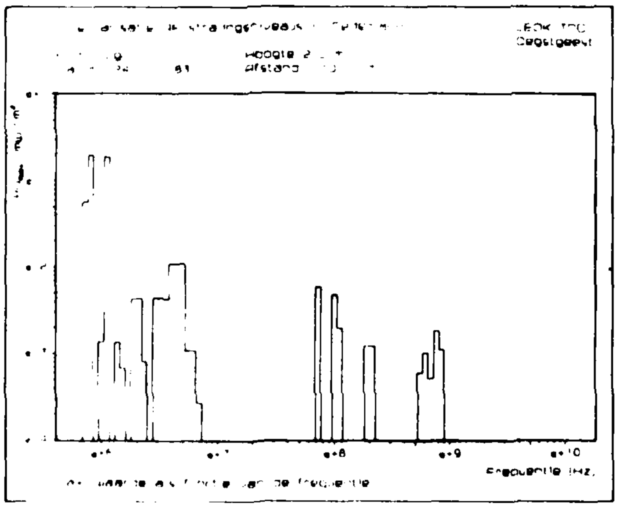
I General	II Antenna	III Transmitter
1. name	11. type	32. power
2. application	12. illumination	33. freq. band
3. info source	13. dimensions	34. p.r.f.
4. location	14. beamwidth	35. duty cycle
|	|	|
10.------	31.------	39.------

Figure 2. List of parameters.

Obtaining the wanted parameter values from the information of the public authorities was a laborious and lasting job. Often it was necessary to use manufacturers' information and estimations, etc. This work has taken much time, more than was expected at the time the job was started. Until now only 150 lists of parameters have been filed. The model still must be validated by measurements. These two areas are the main objectives of future activities.

Some examples of graphical output plots are illustrated in Figures 3, 4, and 5.

(PFD[mW/cm^2])



(Frequency [Hz])

Figure 3. Plot of maximum PFD versus frequency of a subset of transmitters.

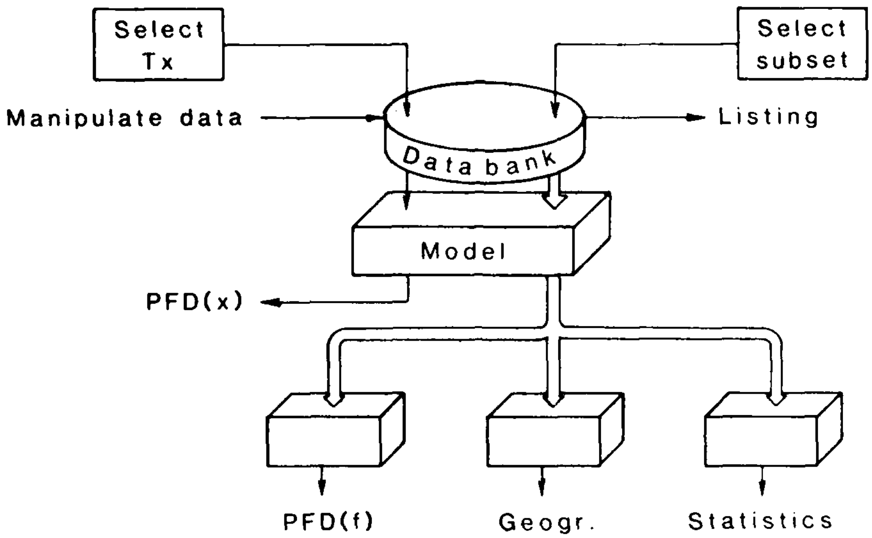


Figure 1. Program structure.

In view of the fact that the accuracy of the input parameters is fairly low, very simple mathematics are used; e.g., near an aperture antenna a constant value for the PFD is assumed. Furthermore, for complex antenna patterns, only the pattern envelope is used. Because of all these approximations, the result of the PFD calculations will reflect worst-case reality

The program of the model is modularly structured so that improvements, extensions, or changes can easily be made. If it turns out that a safety factor is needed (e.g., due to constructive interference because of reflections), this can easily be done.

COLLECTION OF INFORMATION

The first step was to decide which parameters would be of importance; the next, to contact public authorities in order to collect the relevant information. Then from this information the required parameters were derived.

A summarized list of the adopted parameters is shown in Figure 2. The list is divided into three groups, each of which contains specific information. The first group contains general information such as name and application; the second, more information about the antenna; and the third, details about the transmitter. The total number of parameters is 39

INTRODUCTION

This paper outlines the activities carried out in behalf of the inventory of the Power Flux Density (PFD) in the vicinity of civil RF sources in the frequency band of 0.5 MHz to 18 GHz. The following approach has been used:

- develop a computer program that gives a general (theoretical) impression of the RF environment;
- collect information about civil transmitters and deduce relevant technical parameters to be used as input data for this computer program;
- carry out measurements in the vicinity of RF-emitting equipment such as seal machines and diathermy equipment that are too complex to model theoretically.

COMPUTER PROGRAM

The computer program should be designed in such a way that, using the transmitter parameters, it would roughly predict the RF environment; a rather simple free-space propagation model was considered to be satisfacto .

Depending on the completeness of the input data, different approaches are used to calculate the PFD. For instance, if the illumination of an aperture antenna is unknown, the program uses other parameters for estimating the illumination (such as the dimensions of the aperture and the beamwidth).

Further on the computer program should have a possibility for data manipulation such as updating the databank, ranking the transmitters, listing, listing in condensed form, etc. In addition there should be a possibility to plot different graphical presentations:

- PFD as a function of distance of one transmitter;
- maximum PFD as a function of frequency of a selected subset of transmitters;
- a geographical view of transmitter locations;
- some form of statistical information such as the number of transmitters and the distances at which their PFDs exceed a definite value.

All these considerations resulted in the program structure shown in Figure 1 in which the different possibilities are illustrated.

EXPOSURE TO RADIOFREQUENCY FIELDS IN THE NETHERLANDS;
MEASUREMENTS AND EVALUATION

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SUMMARY

During 1982-83, activities have been started to get a survey of the man-made RF environment in The Netherlands. These activities were carried out as commissioned by the Ministry of Housing, Physical Planning, and Environment. The limitation given was that (for the time being) only civil installations in the frequency band 0.5 MHz - 18 GHz preferably had to be included. Within the permitted time frame, it was not feasible to cover all kinds of installations or equipment in this frequency band.

Some specific experimental work as well as literature sources have been used and the results extrapolated to get a general estimation of the Netherlands situation. In a nutshell, the job can be divided into four parts:

- collection of raw information of officially registered equipment;
- out of this raw material, extraction of parameters that could be used as input data for a computer model;
- development of a data retrieval system and a computer model able to convert the input data into RF environmental data;
- field measurements to validate the model and field measurements in the proximity of some unintentional radiators not suitable to be incorporated in the model.

DIELECTRIC BEHAVIOUR OF WATER IN BIOLOGICAL MATERIAL WITH PARTICULAR REFERENCE TO BRAIN TISSUE

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SUMMARY

The absorption of microwave energy by biological material at frequencies in excess of 1 GHz is due mainly to the water content. Knowledge of the dielectric properties of water in biological material is therefore a necessary prerequisite for the calculation of energy deposition. However, the water of hydration immediately adjacent to biological macromolecules is subject to chemical forces different from those in bulk water and must in consequence exhibit different dielectric properties. The nature and proportion of this water vary considerably from one tissue to another and therefore need to be evaluated for each specific case. For adult-rabbit brain material, dielectric measurements show that the water of hydration constitutes about 20% of the total while the remainder has dielectric properties similar to those of pure water. With brain tissue from recently born rabbits, the proportion of water of hydration is indistinguishable from zero.

INTRODUCTION

When radiowaves and microwaves are incident upon a body, the energy deposition is dependent upon many parameters, the chief of which are its shape and size, the dielectric properties, and the frequency of the radiation. More specifically the energy absorbed per unit volume in any small volume within the body is equal to the product of the electrical conductivity and the square of the electric field over that volume. This electric field is related to the external electric field via the dielectric constant (relative permittivity). Consequently the dielectric properties (permittivity and conductivity) of a biological medium need to be known before energy absorption can be calculated.

The general dielectric properties of biological material have been summarised elsewhere (1), and it is known that at frequencies greater than around 1 GHz the microwave energy absorption is dominated by the water content. At 37°C pure water has a relaxation frequency of 25 GHz and is known to obey the Debye equations to a close approximation. All the relevant dielectric parameters of pure water are well known, and the amount of energy deposited by microwaves of a given frequency and field strength can be calculated in terms of these parameters. Such calculations may also be performed for water in biological tissue provided that the correct dielectric parameters are utilised. This is one of the reasons why it is necessary to know the dielectric properties of water in tissue, and in particular how far they deviate from those of pure water. One can go further than this, however. By studying the dielectric behaviour of tissue water, it is possible to quantify the water of hydration and thus provide information on the structure of water in the neighbourhood of the macromolecules comprising the tissue. This layer of bound water is an integral part of the structure, and disruption of it may completely alter the configuration of the macromolecule, as has been observed for DNA (2) and other molecules.

In this paper the state of water in rabbit brain tissue is discussed in the light of recent dielectric measurements (3). The conclusions are compared with those obtained for other tissues and biological solutions, and an attempt is made to summarise the situation for biological material as a whole.

DIELECTRIC BEHAVIOUR OF BRAIN TISSUE

The relative permittivity and conductivity of macerated brain tissue from Dutch pigmented white rabbits have been measured recently (3) over the frequency range 0.01-18 GHz. Full details appear elsewhere (3), but the essential of the experimental technique is as follows. At frequencies up to around 6 GHz a Time Domain Spectrometer was used. This instrument with its various applications has been described previously (4-7). Between 2 and 18 GHz a recently devised frequency domain technique was employed (8).

Excised brain tissue wa[illegible] for rabbits of five different ages - 6-8 hours, 2 days, 9 days, 2[illegible] [illegible]d adult (more than 50 days) - and typically 45 frequency points were o[illegible]ined in the total frequency range 0.01-18 GHz. For studies of the dielectric behaviour of the water component, the data at frequencies in excess of 1 GHz are of particular significance; the values of relative permittivity are shown in Figure 1 for the two extreme ages.

Analysis of the data in Figure 1 shows (3) that they may be represented by a sum of two Debye dispersions, the lower frequency one of which has a dielectric increment, or amplitude, of value 8.8±1.8 and a relaxation frequency of 1.0±0.2 GHz. The other dispersion has corresponding parameters 35.5±0.4 and 25 GHz respectively.

The details of analysis and the dielectric behaviour of the brain tissue at the low frequency end of the range of measurement will not be considered here, but what can be stated is that two dispersions are required to account for the dielectric behaviour of the aqueous component; any attempt to account for the data by a single relaxation region having the same parameters as pure water fails. Therefore brain material, like many other biological systems that have been investigated, has a water component contributing at frequencies lower than pure water. Since a longer correlation time (lower relaxation frequency) means that a higher potential barrier has to be surmounted during dielectric relaxation, this lower frequency component may be identified with the bound water, or water of hydration. The larger, higher frequency component would then correspond to the bulk water. Assuming that the quantity of a dispersing component is roughly proportional to the amplitude (dielectric increment) of the dispersion curve, then the proportion of bound water turns out to be about $8.8 \div (35.5 + 8.8)$, i.e. approximately 20%.

A further verification that the low frequency component corresponds to the bound water is shown by the information in Figure 2. The upper line shows the variation with percentage decrease in moisture content of the percentage decrease in amplitude of the higher frequency component for rabbit brain material of the five different ages studied. The moisture content values were taken from the literature and checked by dry weight measurements after evaporation. The lower line shows the corresponding plot for the sum of the amplitudes of the two dispersions. Reference to the figure shows that it is the lower line that has the required slope of unity, thus verifying the hypothesis that the sum of the two increments corresponds to the total water content and therefore that the dielectric method neatly separates the bound water from the bulk water. An attempt will now be made to see how far possible it is to define a common position concerning the properties of water in biological material in general.

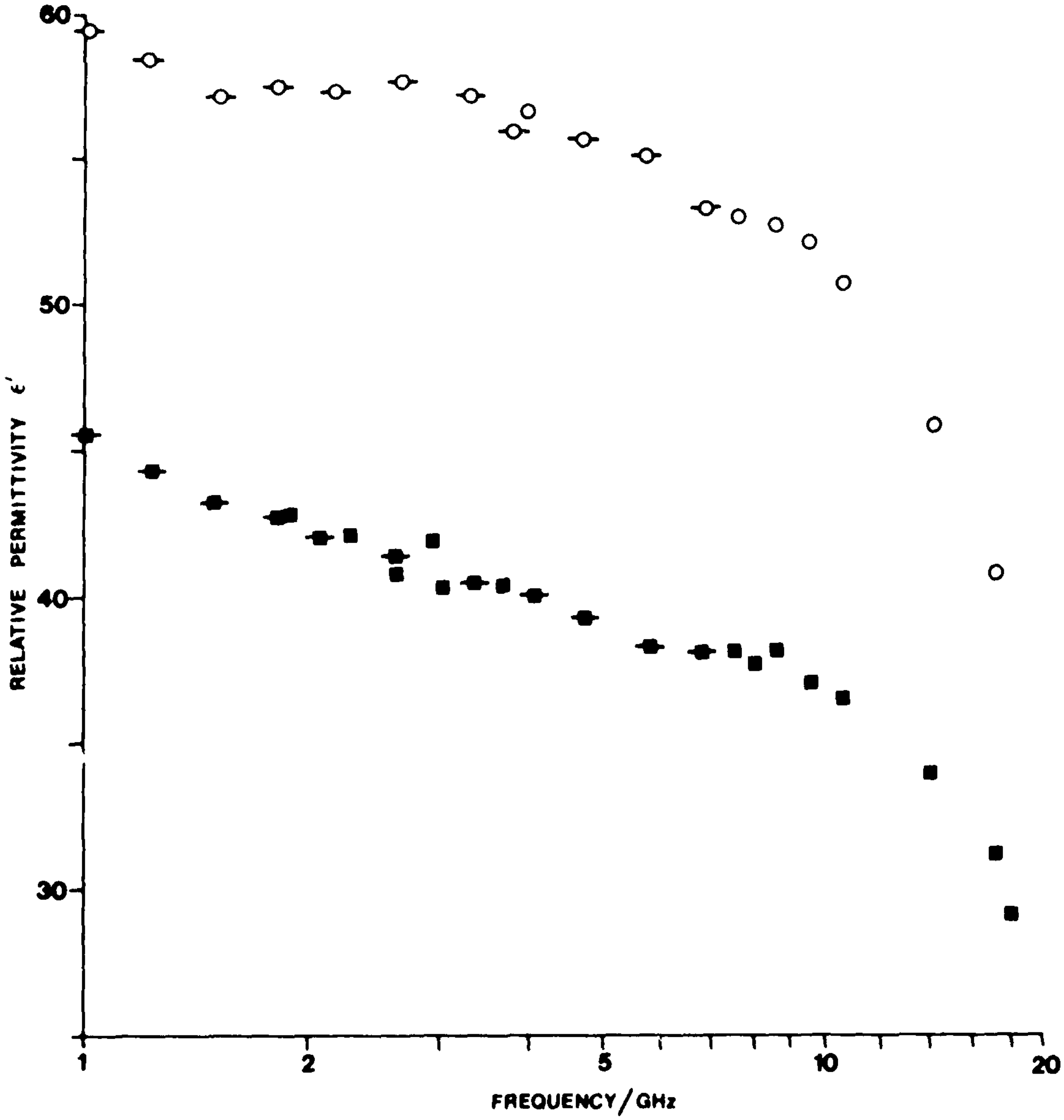

Figure 1. Relative permittivity of rabbit brain tissue at 37°C between 1 and 18 GHz.

O Brain material from newly born rabbits

■ Brain material from adult rabbits

(Horizontal bar indicates points measured on Time Domain Spectrometer; other points were measured on Frequency Domain equipment)

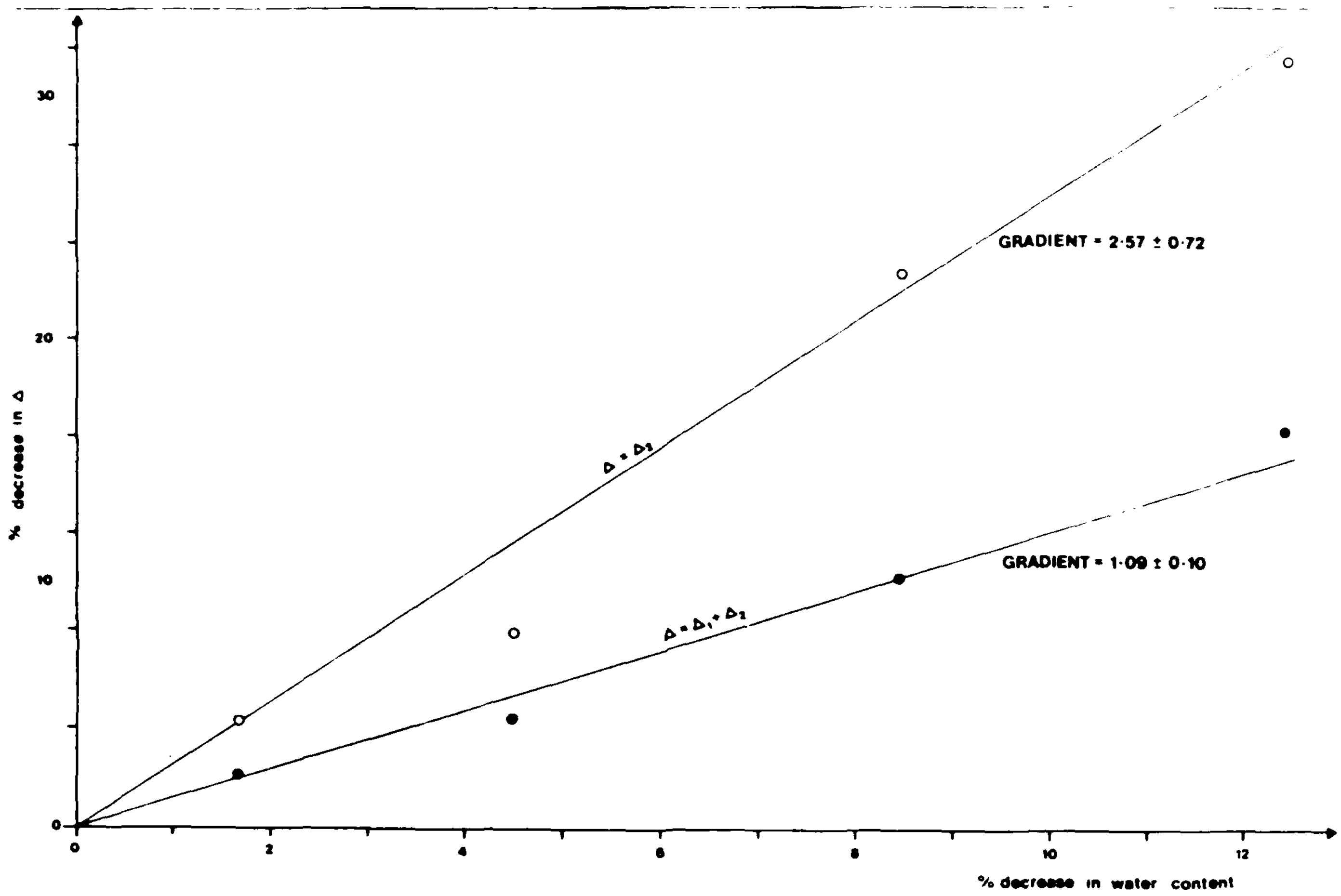

Figure 2. Variation of percentage change in moisture content of rabbit material with percentage change in dielectric increment (Δ) at 37°C.

Δ_2 Higher frequency component (relaxation frequency 25 GHz)

Δ_1 Lower frequency component (relaxation frequency 1 GHz)

DISCUSSION

The foregoing analysis has shown that about 20% of the water present in adult-rabbit brain tissue exists as water of hydration. The rest of the water may be characterised by dielectric relaxation parameters equal to those of pure water; i.e., the bulk water behaves as pure water. By comparison, if an aqueous solution of serum low-density lipoproteins (C=20%) is considered (9), it is found that only 1% of its water is in the bound state. To take a further example, a solution of myoglobin of similar concentration has been shown (10) by dielectric methods to have about 9% of aqueous content existing as water of hydration. Thus although these three different systems have a similar concentration of macromolecules (~ 20%), the proportion of bound water is vastly different between each of the cases. In order to see if there is any unifying principle, it is necessary to look more closely into the nature of bound water and its place within the structure of the various tissues.

There are many different experimental techniques available for measuring water of hydration of globular macromolecules in solution; examples include sedimentation studies, viscosity measurements, diffusion experiments, NMR observations, as well as studies of dielectric behaviour. The conclusion arising from experiments based on all these different techniques is that the results are best explained by the presence of an average of two layers of water molecules tightly bound to the macromolecule. Bearing in mind the diversity in the different experimental techniques, this is an important conclusion which should command general acceptance. Whether there are in addition subtle long-range intermolecular forces is an open question, but there seems no doubt, at least for macromolecules of a globular conformation, about the validity of model of a central molecule surrounded by a shell of hydration whose structure is governed by hydrophilic forces. On the basis of this model it is clear that the larger the macromolecule is, relative to the water molecule, the smaller will be the fraction of bound water in a solution of a given concentration of macromolecules. The differences in the relative proportions of bound water between solutions of low-density lipoprotein and myoglobin (both fairly spherical molecules) of the same concentration are consistent with this model. The situation with regard to brain tissue is different in that, unlike the aqueous solutions referred to above, the nonaqueous components are not distributed uniformly throughout the tissue.

Brain material can be considered as the most structured and complex of mammalian tissues. In adult-rabbit brain tissue the concentration of macromolecules varies considerably from one region to another, sometimes being very densely packed within the cell membranes. Accompanying this situation is a high proportion of intracellular water which is remote, in terms of molecular distances, from water-binding molecules such as proteins, phospholipids, and nucleic acids. It is therefore to be expected that much of the water in brain material exhibits properties similar to those of pure water, while the rest is tightly bound. In contrast, lens nucleus material behaves more like an aqueous solution, consisting as it does of a fairly uniform suspension of crystallins in an aqueous environment; and this is reflected in the observation (11) that the dielectric properties of the bulk water are somewhat different from those of pure water, while the bound water occupies about 20% of the total volume (12).

In summary the following may be said about the state of water in biological material and aqueous solutions of biological macromolecules. With compact, globular macromolecules in an aqueous environment, a shell of bound water of average width about two molecules exists. The quantity of bound water expressed as a weight fraction of the hydrated macromolecule must therefore depend inversely upon the size of the macromolecule. Thus while haemoglobin has a hydration factor of about 0.3 g/g (13), the much larger low-density lipoprotein molecule possesses hydration of less than 0.1 g/g (9). The fraction of the total water volume which is bound can then be calculated from these figures if the concentration of macromolecules is known; it will of course increase with concentration. The implications of this for whole tissue depend upon the tissue structure. For example, with lens material where the structure can be represented to a good approximation as a uniform suspension of globular macromolecules in an aqueous environment, a dielectric behaviour similar to an aqueous solution may be expected. In contrast, for the more complex brain tissue there is no simple model for interpreting dielectric and other experimental data, and the quantity and nature of the water of hydration must be inferred from another approach. The dielectric method offers a means of doing this by equating the bound water fraction with the ratio of the smaller to the sum of the amplitudes of the two water dispersions, as explained in this paper. The efficacy of the method can be further enhanced (14) by cooling the tissue to subzero (Celsius) temperatures, whereby the effects of dispersions due to the nonaqueous components can be eliminated. By such means it is possible to characterise the water of hydration in complicated tissues and macromolecules, and thus further the understanding of the basic mechanism of how radiowaves and microwaves interact with biological material.

ACKNOWLEDGEMENTS

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EVALUATION OF HUMAN EXPOSURE TO LOW FREQUENCY FIELDS

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SUMMARY

The biophysical model concept described in this paper might be suited as a basis of discussion to determine and define limits of exposure to electric or magnetic fields below 100 kHz, including 50/60 Hz.

The electric field strength within the tissue in the environment of excitable neurons and muscle cells is considered decisive for the biological effect. Threshold values of field strength or current density inducing biological effects are compiled from experimental and theoretical studies. On the basis of these data it is possible to establish "safe," "dangerous," and "hazardous" current density curves as a function of frequency. The criterion for the definition of injury is the elicitation of ventricular fibrillation which must be avoided. To define exposure limits, the field strength or current density causing injury should be reduced by a factor of 300. The arguments supporting this wide safety margin are discussed.

In the second part of this paper the electric and magnetic field strength in the human environment is correlated with the corresponding electric current density induced in the human body. This enables "safe," "dangerous," and "hazardous" levels of current density in the human body to be correlated with the external electric or magnetic field intensity. Parts of the concept presented in this paper have been adopted in the DIN/VDE Regulation No. 0848 which defines the limits for frequencies above 10 kHz.

1.0 INTRODUCTION

In the past few years more and more persons have been exposed to strong fields with frequencies below 100 kHz in areas other than power engineering application (16.6, 50, 60 Hz). Magnetic fields have been of special interest due to their penetration characteristics for the human body. Various types of induction heating systems in the low and medium frequency range are examples of sources of strong magnetic fields. Biologic effects occur with a sufficient intensity of the fields; examples include hair movement on the body in strong electric fields or the generation of light and flickering phenomena, and subjective complaints such as headache in strong magnetic fields. In medicine, the effects of strong magnetic fields are being used in imaging processes (nuclear spin tomography) or for therapeutic purposes (magnetic field treatment).

The reason for the uncertainty in determining personnel health limits for frequencies below 100 kHz is that so far a sufficiently secured model idea has not become known for estimating the risk in the frequency range involved here. Such a concept, however, is necessary as one cannot explain that the full frequency range can be studied by experiments with good results similar to those obtained in the sphere of power engineering fields. This paper describes a simple concept that may serve as a basis in the discussion on the definition of personnel health limits. Parts of these ideas and considerations have already been adopted in the VDE regulation (1984) defining limits for frequencies above 10 kHz.

2.0 BASIS OF THE CONCEPT FOR EVALUATING HUMAN EXPOSURE

When possible health risks from the influence of electric and magnetic fields on man are evaluated, primarily those biologic effects are considered which originate from a direct action on the cells in nerve and muscle tissues. The physical quantity determining the biological effect is the electric field strength in the tissue surrounding the living cell. This can be inferred from both theoretical considerations where the depolarization of the cell membrane potential is directly related to the magnitude of the electric field intensity in the cell environment, and from the experiments confirming this concept (Bernhardt, 1983). A great volume of experimental data on stimulus thresholds for different nerves and muscle cells, however, has often been expressed in the form of electric current values and not as field strength values. Only comparatively few papers disclose data on the field strength thresholds. Here, the electric current density will be used as the decisive parameter in assessing the biologic effects at cell level. As far as necessary, the values given for the specific conductivity can be used to convert the current density in the tissues into field strength.

Selection of the current density as a measure of action on the cellular level also offers the possibility to extrapolate conditions in the human body from studies of animal experiments or from measurements taken at isolated cells, by way of mutual comparison of the current densities. It is irrelevant whether the electric current density surrounding a cell is introduced into the body through electrodes or induced in the body by external electric or magnetic fields; however, the current paths within the body may be different.

In the evaluation of human exposure to electric and magnetic fields below 100 kHz, the following steps are relevant:

a) Experimental data on the thresholds for stimulation of excitable cells are combined in a current density/frequency diagram. A current density "envelope" is used as the "threshold curve of possible acute health hazard"; another current density curve is plotted as the "injury threshold."

b) Some experimental values in relation to phenomena depending on current densities below the stimulus thresholds, in combination with theoretical considerations, define a current density curve below which a direct influence on neurons can no longer be expected ("limit of the safe range").

c) The current density curve between the "safe" and the "dangerous" current density curves may serve as the limit value curve in evaluating exposure to external electric and magnetic fields.

d) Electric and magnetic field intensities in man's environment are related to the electric current densities they induce within the human body. This allows correlation of the internal current density curves with the external field strengths, and definition of "safe" and "dangerous" field strengths.

e) It must be verified that no direct or indirect biological effects are caused by other mechanisms which could also be a hazard to man at lower field strengths than those defined in d).

3.0 DEFINITION OF "SAFE" AND "DANGEROUS" CURRENT DENSITIES

In this section I consider threshold values of the electric current density for different biological effects in nerve and muscle tissue. The values are summarized in the current density/frequency diagram of Figure 1. A more profound treatment is given by Bernhardt (1983).

3.1 Stimulation Thresholds

3.1.1 Stimulation of Sensory Receptors

Curves a_1 and a_2 in Figure 1 give threshold values for the stimulation of sensory receptors taking place immediately underneath the surface electrodes (Geddes et al., [illegible]).

3.1.2 Disturbance of Cardiac Stimulation

When electric field intensities in the environment of myocardial cells are sufficiently high, the process of intracardial stimulation can be influenced. Two processes are relevant here: extrasystoles, and atrial and ventricular fibrillation. While premature heart contractions in the cour of the regular pulse sequence are deemed disturbances of the cardiac stimula ion, ventricular fibrillation is the most frequent acute cause of death in the electrical accident. Even though there are numerous studies on current intensity, duration of exposition, and current path in electrical accidents, information on the field strength or current density values leading to disturbance in cardiac stimulation can hardly be found.

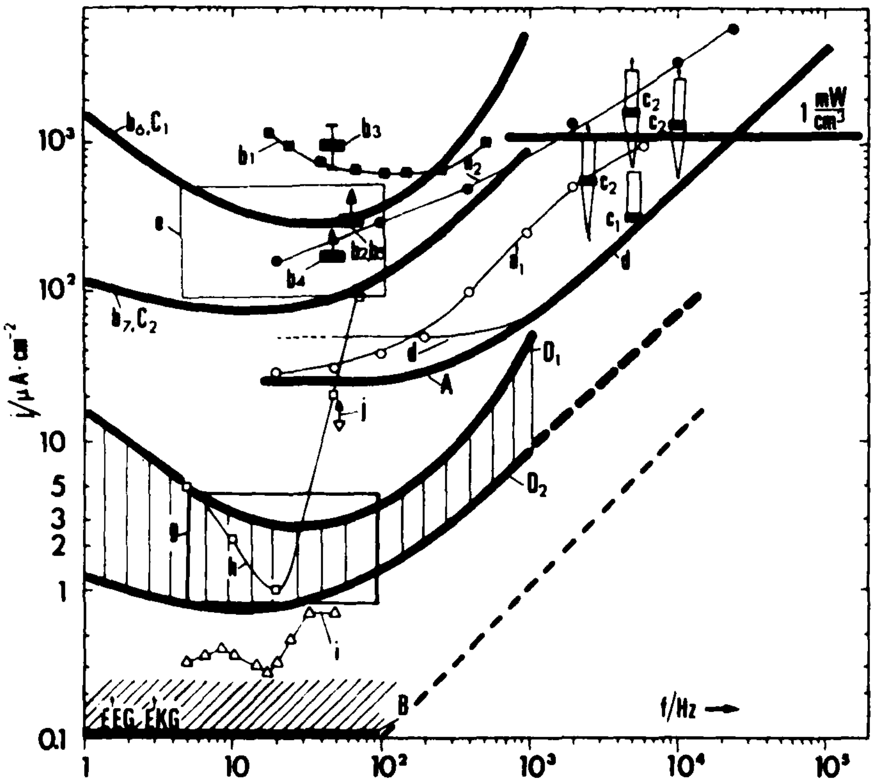

Figure 1. Threshold values of the electric current density for different biological effects. Explanations are given in the text.

In view of the "worst case" event, the risk of ventricular fibrillation increases with the duration of the current flow. With a current flow duration of a single period, more than 100 mA are necessary to elicit fibrillation; whereas with a duration of 100 periods, the fibrillation threshold ranges about 0.7 mA (Roy et al., 1977). Therefore further statements will be based on exposition times of 1 second or longer. Thresholds for fibrillation elicitation are higher than the stimulation thresholds for extrasystole elicitation, by the factor of 3 to 5 (Antoni, 1982, Weirich et al., 1982).

The biophysical basic mechanisms involved in creation and further course of ventricular fibrillation in studied animal hearts are the same as the mechanisms to be found in the hearts of bigger animals, so information on the electric field strengths for the current densities in the tissue allow results obtained in animal experiments to be interpreted to the human body. The following thresholds of current densities for ventricular fibrillation have been found:

- Irnich et al. (1974) measured the stimulation and fibrillation thresholds with dogs and recorded these values as a function of the frequency (16-300 Hz , b_1 in Figure 1).

- Roy et al. (1976), using cardiac catheters, found the threshold values to be above 300 $\mu A/cm^2$ (b_2 in Figure 1) - depending on the catheter size.

- Jacobsen et al. (1974) measured the field intensity at pig hearts and quoted a confidence range for the electric field strength threshold to elicit ventricular fibrillation between 224 and 429 mV/cm (mean value 327 mV/cm). The current density values converted for a myocardial conductivity of 0.25 S/m are plotted under b_3 in Figure 1.

- Osypka (1963) quoted a threshold value of 8 V/m as sufficient to start the stimulation process at the heart. Calculation and conversion lead to a current density of 2.0 A/m^2 (200 μA/cm^2, b_4 in Figure 1).

- Studies with the human heart by Watson et al. (1973), using 1.8-cm^2 electrodes, resulted in a threshold of 300 μA/cm^2 to elicit ventricular fibrillation (b_5 in Figure 1).

- The current values quoted by Weirich et al. (1982) for the stimulation threshold and the fibrillation threshold with 1 second of stimulation are plotted in Figure 1 as current density curves in a manner that the curves roughly correspond to the data obtained by other authors (Curve C1: fibrillation threshold; curve C2: diastolic stimulation threshold). As a result of this procedure, the uncertainty in relation to the shape of these curves --related to the human body -- is a factor of 2 or even more.

3.1.3 Stimulation of Isolated Cells

Using microelectrodes, several authors measured the thresholds of the current for extracellular stimulation of isolated neurons, with varying spacing of the microelectrode from the cells. Current density values for the stimulation thresholds can be calculated from these current intensity/spacing measurements.

There is a great variability between the individual studies, possibly due to different spacings from the next node of Ranvier. Some of these measurements have been interpreted (Ranck, 1975, c_1 and c_2 in Figure 1).

The extracellular stimulation experiments with isolated cells confirmed the theoretical concepts (Bernhardt, 1973) that substantially smaller current densities are required for stimulation of an excitable cell with parallel orientation of the electric field strength than with normal orientation.

3.1.4 AC Stimulation Threshold

Schaefer (1940) quoted a formula to express the stimulation threshold for nerve/muscle systems as a function of frequency. The formula gives the stimulation threshold of alternating current in the form of a threshold ratio to the 50-Hz threshold for different frequencies. There is a linear threshold increase with a frequency increase in the high frequency range. Here reference is made to current density values. When a 50-Hz threshold of 0.5 A/m^2 is selected, the current density ranges for isolated-cell stimulation, designated by (c) in Figure 1, are just above that curve (curve d in Fig. 1).

3.1.5 Induction of Membrane Potentials by Electric Fields Surrounding a Cell

A threshold value for stimulating effects of roughly 300 μAcm^2 must be expected for theoretical reasons too. As a result of charge transfers inside and outside the cells, alternating electric fields induce a membrane potential

in biological cells, which is determined not only by the strength and frequency of the field but also by the size and shape of the cell and its orientation in relation to the electric field (Bernhardt, 1973). The field-induced potential difference was measured by using intracellular microelectrodes (Bernhardt, 1983). The measured values confirmed the theoretical value. From the theoretical relationship the field strength in the cell environment can be calculated for a variation of the membrane potential by 10 mV, which may result in a stimulation effect in excitable cells. The magnitude of the corresponding current density range is identified by range e in Figure 1.

3.2 Hazardous Current Density Curves

As conclusion of chapter 3.1, curve A in Figure 1 can be considered the "envelope" which delimits the experimentally found current density values for stimulating effects. Current densities produced by electrodes or induced by external electric or magnetic fields may result in a stimulation effect on neurons and muscle cells with values above the plotted curve A. An unexpected stimulation of muscle cells may lead, for instance, to a situation of fright that can trigger a hazard. When, after a considerably long duration of influence by current densities above the "envelope," cerebral nerves in major spheres are stimulated at the same time, acute neurologic symptoms cannot be excluded (e.g., increased blood pressure, convulsions in vessels, spasms of the breathing system, paralyses). In this sense, Curve A may be called the "threshold curve for a possible hazard."

The higher density curve C_1 is used here as the "threshold curve of injury." Ventricular fibrillation in the sense of a definition of the injury is considered here to be that event which must be avoided. A sufficiently wide safety margin must be selected when personnel health limits are defined.

With higher frequencies, the threshold values for stimulating effects are close to current densities that result in a thermal effect. A current density of roughly 1 mA/cm^2 generates a specific absorption rate of 2 $mW \cdot cm^{-3}$ in the tissue (specific conductivity of 0.2 $S \cdot m^{-1}$), which may result in a rise in temperature by 1 °C in muscle tissue over a period of 1 hour (without consideration of thermal transfer by thermal conduction and blood circulation). With a current density of 5 mA/cm^2 (reached with curve A at 100 kHz), the same heating effect occurs in less than a few minutes. The comparison shows that an injury possibly occurs as a result of a stimulating effect rather than a thermal effect for a short period of time, with frequencies up to the range from 30 to 100 kHz.

3.3 Biological Effects with Current Densities Below the Stimulation Thresholds

Electrophysiologic studies have shown that information can be transferred between neuronal elements even without action potentials (Schmitt, 1976). Minor potential variations of 0.1 mV in one neuron may influence the activity in other neurons by a synaptic effect. Today the view prevails that in the brain small graded potential variations in the range of 0.1 mV are important in many processes. It must be expected, therefore, that current densities in electrical events in the brain, which are below the stimulation thresholds, may influence functions of the brain. As experimental studies in this direction could so far hardly be carried out, an attempt should be made to delimit the range in question on the basis of a small quantity of data only.

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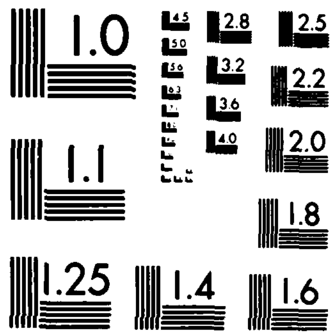

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

3.3.1 Electro- and Magnetophosphenes

The generation of light effects (phosphenes) under the influence of electric currents or magnetic fields has been known for a long time. Lövsund et al. (1980, 1981) localized the mechanism to certain areas on the retina.

Adrian (1977) measured the threshold current intensities for phosphene generation with alternating currents of different frequencies. As one electrode was applied directly at the eye of the test subject, Adrian was able to give the minimum current density for the generation of phosphenes. Adrian's data is plotted in the form of curve h in Figure 1.

Silny (1981) studied the subjective perception of flicker phenomena in volunteers expcsed to strong low-frequency magnetic fields. With a homogeneous magnetic field being generated by a Helmholtz coil arrangement, the electric current density in the peripheral spheres of the heat (eye, cerebral cortex) can be estimated (curve i in Figure 1). The magnetic current densities determined here are below the threshold density of 3 $\mu A/cm^2$ quoted in literature for biologic effects, but this may be due to the method of calculation.

3.3.2 Variation of Reaction Potentials in Low-Frequency Magnetic Fields

Silny (1981) examined test persons to study the influence of 50-Hz magnetic fields on optically generated reaction potentials. A 50-Hz magnetic field with an induction of 60 mT changes the polarity of the observed reaction potential, corresponding to a magnetically induced current density of roughly 14 $\mu A/cm^2$ in the cerebral cortex (j in Figure 1).

3.3.3 Field-Induced Potential Differences of 0.1 mV

The idea outlined in section 3.1.5 is adopted here with a shift downward by the factor 100 of the range e of Figure 1 between 1 and 100 Hz (now 0.1 mV instead of 10 mV potential difference). The current density range g in Figure 1 must be assigned to field-induced potential differences in the range of 0.1 mV within this frequency range.

If potential-difference variations of this magnitude should be the cause of certain biologic effects that have been noted, the corresponding thresholds for the current density ought to come under the magnitude of 1-_ $\mu A/cm^2$. The relevance of field-induced potential differences of 0.1 mV, however, needs further and more specific explanation by continued studies and experiments.

3.4 Safe Current Density Curve

One may estimate "safe" field-induced current densities by considering the naturally flowing currents in the brain as a result of the electrical events in the brain. The measured values, which are recorded using extracellular electrodes on the cortex surface (typical values 50-100 μV with 1-cm electrode spacing), furnish a current density of roughly 0.1 $\mu A/cm^2$. The current densities within the brain may vary strongly at a microscopic level--depending on the cerebral nerve anatomy--and may well be as high as 10 to 100 $\mu A/cm^2$, e.g., on the surface of cells that are electrically active at the time of measurement. The comparison against the naturally flowing currents, in combination with the frequency range from 1 to 100 Hz, leads to the

conclusion that brain current densities due to external electric or magnetic fields or generated through electrodes should have no influence on neurons when the current densities remain below 0.1 $\mu A/cm^2$ approximately.

This limit is indicated by curve B in Figure 1. This curve may be considered to be a "curve of the limits of the safe range." Biologic effects as the consequence of direct action of electric fields onto neurons must be expected above this curve, and their existence has been demonstrated in the range between 5 and 100 Hz.

3.5 Limit Value Curve

Curve D_2 in Figure 1 is suggested as the limit value curve in evaluating human exposure to external electric and magnetic fields. The safety margin from curve C_2 is 100. Additional theoretical and empirical studies will have to demonstrate whether this safety factor is open to reduction or whether the factor must be increased.

A particular importance must be awarded to the brain as the most important switching and control center of the body. Today the view prevails that small potential variations below the depolarization processes required for action potentials have a role in many cerebral functions which is greater than has been assumed so far.

Some experimental results have shown (cf. section 3.3) that, in the low frequency range, effects occur with current densities below the stimulation current densities by a factor up to 100. Further information is urgently needed in this respect, mainly to demonstrate whether the health condition will be impaired by long-term exposure to current densities in this range. Here, too, the field intensity or current density in the brain should be known so that the results gathered in animal experiments can be transferred to the human body. The comparatively wide safety margin takes the following points into consideration:

- There is an uncertainty in relation to the current density values that are required for elicitation of extrasystoles and ventricular fibrillation.

- The majority of the threshold value data originates from animal experiments. The translation of this data to conditions in the human body needs more detailed definition.

- Regarding the stimulation thresholds, the varying individual sensitivity as well as the increased sensitivity in persons with manifest disturbance in stimulation of the heart must be taken into account.

- Because of insufficient long-term experience, safety factors are required. The subjective complaints reported so far after exposition for an extended period of time (such as headache) result in current density values below the fibrillation thresholds by a factor between 10 and 100. Such current densities should not be exceeded in relation to the brain.

- With the selected safety factor, moreover, current densities such as those occurring in the low frequency range during therapeutic magnetic field treatment will be precluded.

- As human exposition to electric or magnetic fields is discussed, there is a substantially higher uncertainty with the precise paths of the field-induced currents than with galvanic current supply into the human body.

- The data on conversion of external electric and magnetic fields into current density in the body involve different assumptions and premises that must be balanced with the safety factor.

4.0 BODY CURRENT DENSITIES INDUCED BY EXTERNAL LOW-FREQUENCY FIELDS

This section quotes the external electric field strengths (E_a) and magnetic field strengths (induction B_a) which, as a function of frequency, induce certain mean electric current densities in the human body. On the one hand, the current densities for the heart and its environment are analysed; on the other hand, the human head, with the brain as the most important switching and control center of the body, will be dealt with as another "critical" organ. Curves A, B, C_2, and D_2 of Figure 1 are translated into field intensity/frequency diagrams, employing the following findings and data:

Studies on distribution of the electric field in homogeneous spheres (radius R) exposed to a plane electromagnetic wave, show that with frequencies below approximately 30 MHz and in biologic material (characterized by ϵ and σ), the electric field strength in the sphere is composed of an electric term E_i^E and a magnetic term E_i^B (Lin et al., 1973; Bernhardt, 1979):

$$E_i^E = \frac{3\epsilon_0 \cdot \omega}{\sigma} \cdot E_a = \bar{A}_k \cdot \frac{f}{\sigma} \cdot E_a \tag{1}$$

wherein $A_k = 6\pi\epsilon_0$ and

$$E_i^B = \pi \cdot f \cdot R \cdot B_a \quad \text{(for sinusoidal fields)} \tag{2}$$

Corresponding studies with ellipsoids (Johnson et al., 1975; Durney et al., 1975) have shown that there, too, in a rough approximation, the external electric and magnetic fields may be considered separately and independently of each other.

Elongate spheroids with longitudinal axes parallel to the external E vector must be deemed the "worst case" with external electric fields. For this reason, the electrically induced field intensities in the body can be determined from information on the total of the absorbed power P for which values are at hand.

Further information from studies on the distribution of the electric field or the absorbed power in different parts of the human body have shown that with frequencies below 10 MHz, the internal field intensity increases directly proportionally to frequency with a predetermined external electric field strength (Gandhi et al., 1979). This means that the application of a suitable value for $\bar{A}$ is possible in the relationship between the internal and the external field intensity Gl (1).

Regarding magnetically induced current densities, the cardiac region and the brain are each considered as homogeneous spheres. The resulting current densities are as follows:

$$j^E = \bar{A} \cdot f \cdot E_a \quad (3)$$

$$j^B = \Pi \cdot R \cdot \sigma \cdot f \cdot B_a \quad (4)$$

(The current densities must be added vectorially when both an electric and a magnetic field are present.)

With suitable values for $\bar{A}$ and σ, electric current densities for the head and the cardiac region, with external electric and magnetic fields and frequencies below 100 kHz, are calculated separately using the equations (3) and (4) above.

4.1 Electrically Induced Current Densities

Calculations of the power absorbed in so-called block or cell models of the human body have been applied in determining the constants A for the cardiac region and the brain. Data originating from different authors and values of $\bar{A}$ are summarized by Bernhardt (1983).

The constant $\bar{A}$--and thus the current density--in elongate spheroids or in the head of block models is 10 to 20 times higher than the current density in the simple spherical model.

Apart from data from studies on the absorption in the high-frequency range, and beside the employment of the extrapolation method within the quasi-static range, A was determined also by calculating the current densities for the head and the thorax on the basis of the field strength measured on the body surface at 50/60 Hz (Kaune et al., 1980; Schneider et al., 1974). The $\bar{A}$-values, determined by entirely different methods, coincide; the factor of variation is as low as 2. As the problem here is only the determination of the magnitude of the body current densities, the same value, $\bar{A} = 3 \cdot 10^{-9}$ S$\cdot$Hz^{-1} $\cdot$ m^{-1}, was applied in relation to the cardiac region and the head.

Figure 2 shows the values of the electric current density, applied to the cardiac region and to the head, as a function of frequency and the external electric field strength. The curves B, D, and A have been transferred from Figure 1, using equation (3) above, to Figure 2. The ordinate is plotted up to the value that is generally deemed the value of ionization of the air (roughly $3 \cdot 10^6$ Vm^{-1}).

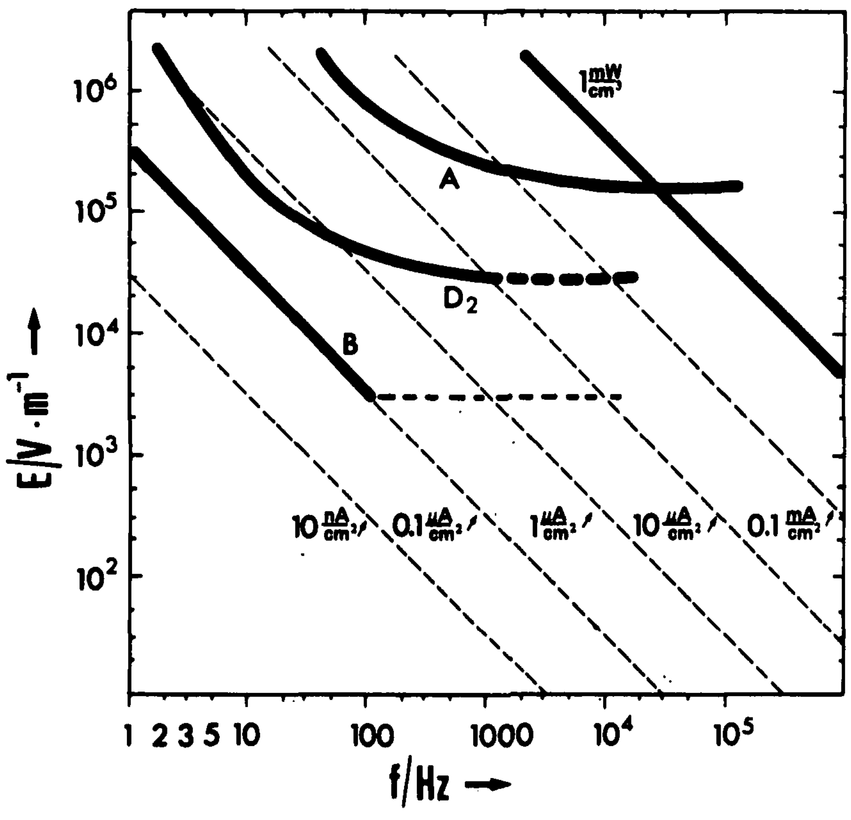

Figure 2. Electric field strength in man's environment, which induces approximately the indicated current density in the head and in the cardiac region (longitudinal axis of man parallel to orientation of the field; the numerical values given for the field strength apply to the undisturbed field).

Curve A: threshold value curve for stimulating effect

Curve B: limit curve of the safe range

Curve D: limit value curves with a sufficiently wide safety margin from the curve plotting the hazardous values

4.2 Magnetically Induced Current Densities

Different authors give different values for the low frequency conductivity of the myocardial tissue and the nerve tissue. In the model calculations set out here, differences in conductivity of the white and grey cerebral substance and the anisotropic nature of conductivity at frequencies below approximately 10 kHz are left out of consideration. A value of 0.2 $S \cdot m^{-1}$ has been used for the specific conductivity of the cerebral substance, while a value of 0.25 $S \cdot m^{-1}$ has been used for the myocardial tissue.

For R in equation (4), values of 7.5 cm for the head and 6 cm for the heart were substituted. As a result of the selection of σ, the products $\sigma \cdot R$ are equal for the heart and head; therefore, the current densities in the heart and in the brain may be presented by a single representation.

Figure 3 represents these current density values as a function of frequency and of the external magnetic field strength (magnetic induction). By application of equation (4), the curves B, D_2, A, and C_2 have been transferred from Figure 1 into this diagram. The values given for the current densities are applicable only to the peripheral regions of the heart or the head, e.g., in relation to the cerebral cortex, following the definition of equation (4). For zones closer to the center of the heart or the head, high values for the magnetic inductions are necessary to induce the same current densities.

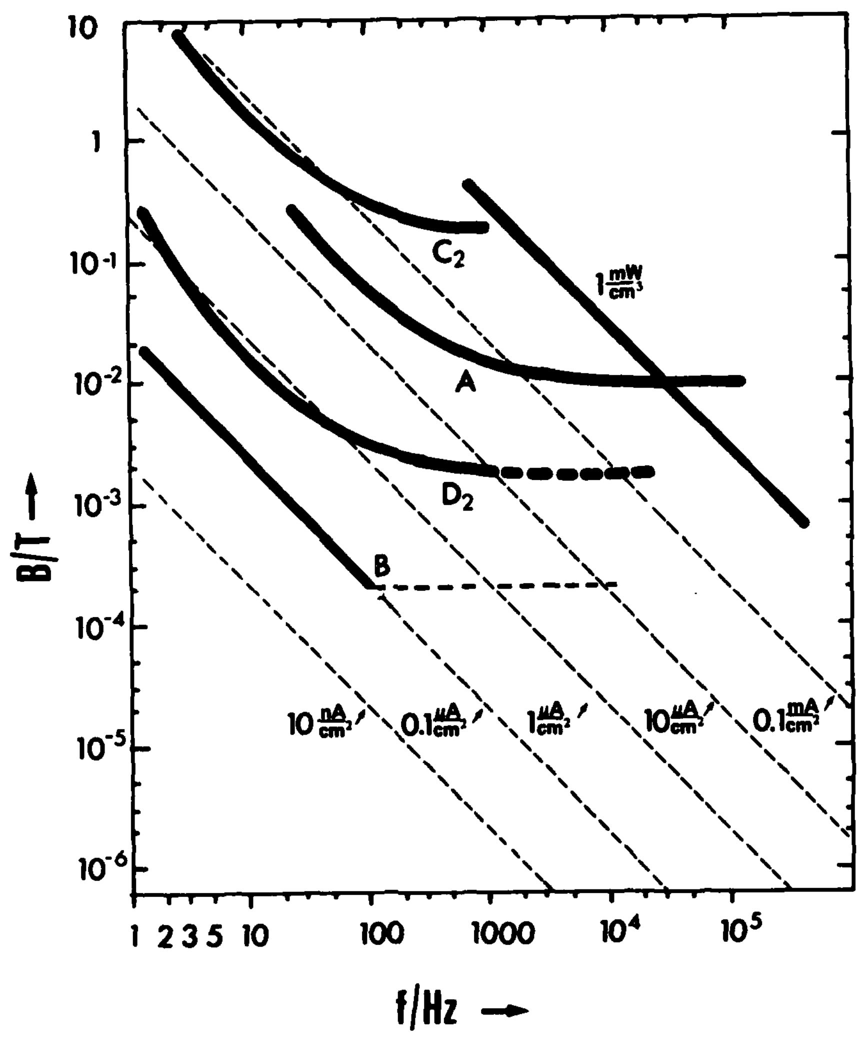

Figure 3. Magnetic induction in man's environment with sinusoidal variations of the field in relation to peripheral regions of the head and the heart, which induce the indicated current densities.
Curve A: threshold value curve for stimulating effects
Curve B: limit curve of the safe range
Curve C_2: diastole stimulation threshold
Curve D_2: limit value curves with a sufficiently wide safety margin from the curve plotting the hazardous values

5.0 CONCLUSIONS

The field strength/frequency diagrams initially permit a rapid orientation about the respective mean electric current densities that will have to be expected in the human head or heart, with predetermined external electric or magnetic field strengths as a function of frequency. The diagrams can be likewise applied to the exposure to fields in the power engineering range and to other frequencies. When the ordinate is used to plot the magnetic induction, the ordinate origin must be shifted upward or downward, in accordance with equation (4), for other radii or other conductivity characteristics.

The explanations given in section 3 on the relevance of curves B, D_2, and A, as well as on the safety factor, are equally valid here by way of analogy. Figure 2 shows that the stimulation threshold curve A can practically not be reached in case of exposure to external electric fields, as the required values of the electric field intensities are excessively high. Conditions are different, however, with magnetic fields. Industrial metal smelting and processing requires magnetic induction at levels far above the curve A. According to some measured data, the values required for stimulation of neurons are not reached, however, at working places. With values of the electric or magnetic field strength below curve B, an influence on neurons is not expected. In the event that biological effects should be noted with such field intensities, these effects must be based on action mechanisms other than those so far described. This is an important conclusion.

The statements given here are confirmed for the power engineering range of 50-Hz electric fields in so far as extensive laboratory and epidemiologic experiments and studies, so far carried through with both animals and test subjects with electric field intensities up to roughly 20 kV/m and with magnetic induction values of 0.3 mT, did not reveal any indication of effects involving a health hazard or affection (Bridges et al., 1981; Schaefer, 1983; Suess, 1981; UNEP, 1984).

When the limit value curve D_2 is used to evaluate human exposure to external electric and magnetic fields or as a basis of discussions on the definition and determination of personnel health limits, attention must be drawn again to the fact that Figures 2 and 3 are suited only to give an idea of the magnitude of the current density in the body. Mean values were taken as the basis to determine the distribution of the electric field in the heart and head; the exact current paths are not known. Local increases of the internal field intensity cannot be precluded. The extent of locally excessive field intensities needs further elucidation by continued study. Safety factors can be defined more precisely only by further studies. Long-term studies with animal experiments and epidemiologic examinations of personnel are particularly important methods.

One second (1 heart period) should be taken as a base for the exposure time for which the field strengths should be averaged. For shorter exposure times, higher values of field strength may be accepted. For exposure of the extremities to magnetic fields, special considerations are necessary, leading certainly to higher limiting values for the field strength.

The model described here, however, does not furnish any statement on the extent to which other factors and secondary effects must be considered in arriving at limit values. Examples are surface effects or currents flowing in

the body when metal objects are touched in which potentials are induced (burns and micro shocks; Gandhi et al., 1982); also the influence of fields on life-saving installations, pacemakers, etc. The evaluation of field strength levels that lead to perceptible but harmless effects may be different for the general population and for occupational exposure. It may be possible to eliminate perceptible effects for workers by suitable technical measures or to inform them of the secondary effects.

Levels of exposure of the general populations should be limited to values low enough to avoid perceptible effects, even if harmless--at least for their dwellings where a continuous exposure of persons cannot be excluded.

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RADIOFREQUENCY RADIATION SAFETY GUIDELINES IN THE FEDERAL REPUBLIC OF GERMANY

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The main goal of this summarized report is to present the German Safety Rules as published a few weeks ago and to provide some background information. Fundamental theory which led to these regulations will not be treated because it is based on what is pointed out in detail in the preceding papers by Profs. Durney and Bernhardt in this volume.

Safety guidelines in the fields of electricity and electronics in Germany (FRG) are usually developed as VDE[1]-rules and worked out by committees, subcommittees, or working groups of the German Electrotechnical Commission within DIN[2] and VDE. These rules are well known in Germany and respected as Technical Rules. They are, in fact, more than a code of practice--they serve as standards comparable to the ANSI standards in the United States for instance.

The standard to be presented here is registered as DIN 57848/VDE 0848 and is divided into four parts:

Part 1: DIN 57848/VDE 0848 Part 1
Hazards from Electromagnetic Fields
Methods for Measurement and Calculation

Part 1 includes instructions on how to take measurements and how to do calculations for getting comparable results. This part is valid since 1 February 1982.

Part 2: DIN 57848/VDE 0848 Part 2
Hazards from Electromagnetic Fields
Protection of Persons in the Frequency Range from 10 kHz to 3000 GHz

Part 2, which is of interest here, is valid since 1 July 1984. It is concerned mainly with direct effects, excluding indirect effects, respectively referring to other standards (e.g., VDE 0866, which deals with shock-hazard voltage).

Part 2 of the standard does not treat prosthetic devices (e.g., pacemakers and/or other electronics) because these questions are still in discussion.

Part 3: DIN 57848/VDE 0848 Part 3
Hazards from Electromagnetic Fields
Protection against Explosive

[1] VDE = Verband Deutscher Elektrotechniker (Association of German Electrotechnicians)

[2] DIN = Deutsche Industrie Norm (German Industrial Standard) and Deutsches Institut fuer Normung (German National Bureau of Standards)

INTRODUCTION

DND has defined a radiofrequency radiation (RFR) safety program. The program administration is outlined in a Canadian Forces Administrative Order [1] and the technical aspects are explained in a Canadian Forces Technical Order (CFTO) [2].

The scientific basis of the program is essentially the same as that of the current civilian standards in Canada [3] and the United States [4]. The DND RFR safety standard may be explained as follows:

(1) The permitted exposure levels (PELs) for radiofrequency radiation workers should not be exceeded. These limits are given in Table 1.

TABLE 1. PERMITTED EXPOSURE LEVELS FOR DIFFERENT EXPOSURE TIMES AND FREQUENCY RANGES*

Frequency Range	Permitted Exposure Levels (PELs)** (mW/cm^2)		
	1 hour	6 min	1 min
1 MHz - 3 MHz	33	66	165
3 MHz - 10 MHz	5	10	25
10 MHz - 1 GHz	1	2	5

* Data taken from Fig. 3-1 of [2]
** PELs depend on the time over which they are averaged

(2) The exposure of a person near a manpack transmitter occurs in the "near field" of the antenna. In this case, the permitted exposure levels must be converted to units of squared electric and/or magnetic field strengths. Since the electric field is considered more important for safety, and since it is the only field that can be measured at 2 MHz with commercial instruments, this report will deal only with electric field strength measurements in the near field of the antenna. The power-density exposure limits of Table 1 may be converted to squared electric field strength figures using Table 2.

RADIOFREQUENCY RADIATION SAFETY OF TWO MANPACK TRANSCEIVERS (AN/PRC-515 AND AN/PRC-77)

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SUMMARY

The radiofrequency radiation (RFR) safety of two Canadian Forces manpack transceivers (AN/PRC-515 and AN/PRC-77) has been studied by a university contractor. This note explains the relationship of his study to current thinking in the field of RFR safety, summarizes his main findings, and applies them to DND operations. It is concluded that both transceivers are safe under all practical operating conditions.

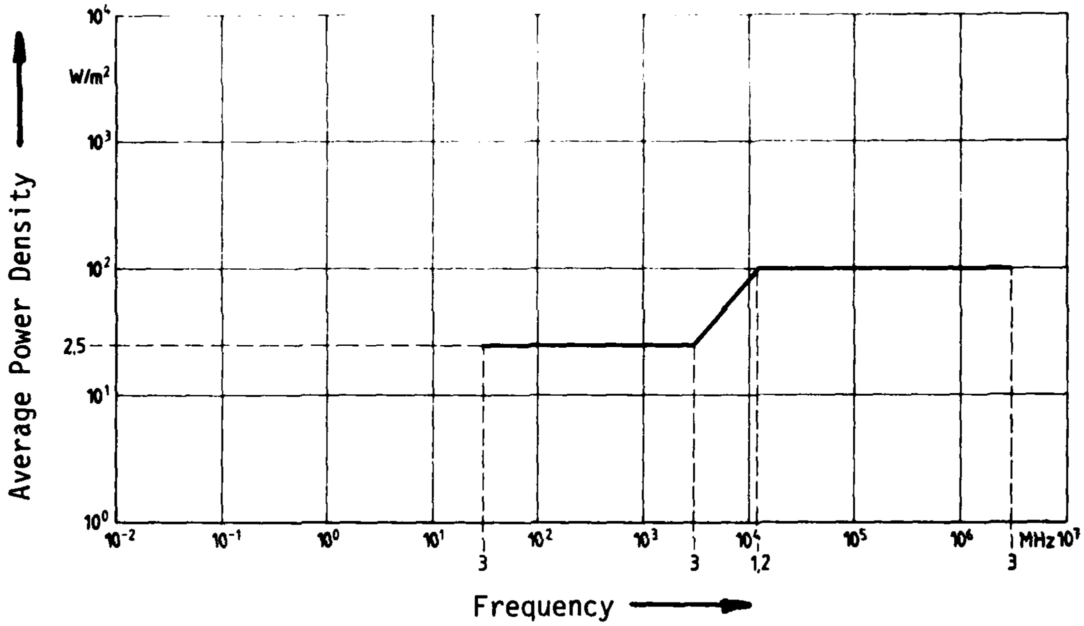

Fig. 3. Maximum permissible power density in the frequency range 30 MHz ≦ f < 3000 GHz during exposure to the electromagnetic field ≧ 6 min

QUOTED STANDARDS

DIN 57 848 Part 1/ VDE 0848 Part 1	Hazards of Electromagnetic Fields: Methods of Measurement and Calculation (VDE-Rule)
DIN 57 866/ VDE 0866	Safety Regulation for Radio Transmitters (VDE-Rule)

EXPLANATION
Working Group 764.0.3 and Committee 764 of the German Electrotechnical Commission within DIN and VDE (DKE) have developed this standard, characterized as a VDE-rule. Basic considerations and findings which have led to the establishment of this standard are found in detail in the report by Profs. Bernhardt, Dahme, and Rothe, "Hazards to Persons from Electromagnetic Fields", published in STH report No. 2/1983 (Journal Series, Federal Health Department, Institute for Radiological Health)

INTERNATIONAL PATENT CLASSIFICATION H 02 H 1-00

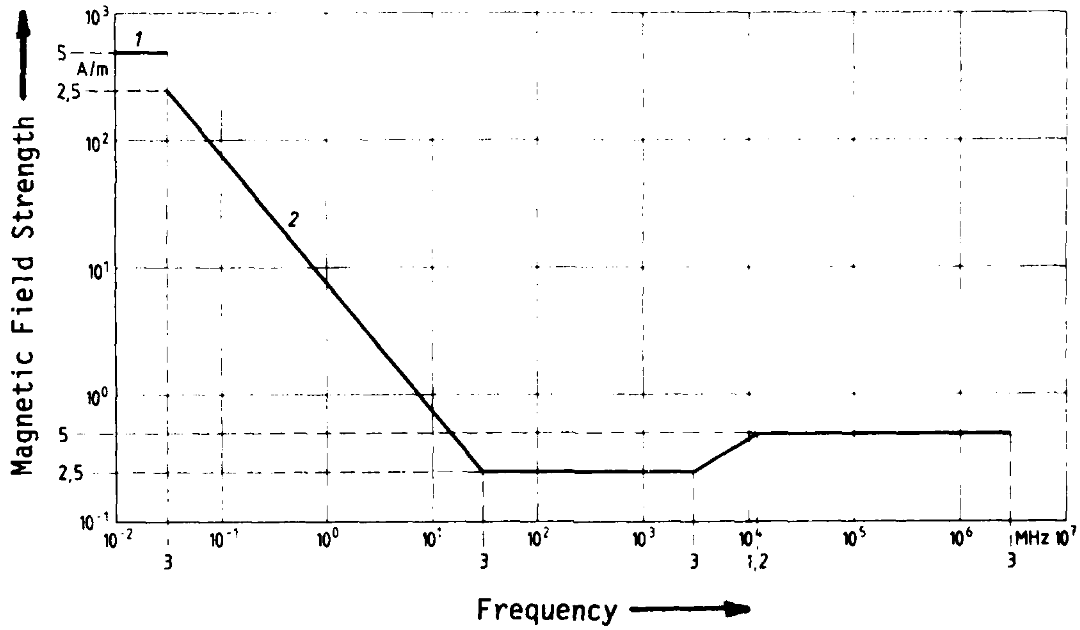

Fig. 2. Boundary value of the magnetic field strength

1. Maximum peak value of the magnetic field strength in the frequency range 10 kHz ≦ f < 30 kHz.
   350 A/m is permissible as the maximum effective value for sinusoidal waveforms.

2. Maximum permissible effective value of the magnetic field strength in the frequency range 30 kHz≦ f< 3000 GHz during exposure to the electromagnetic field ≧ 6 min.

Author's comment:
Referring to DIN 56 848 Part 1/VDE 0848 Part 1 throughout this VDE-rule (Part 2) the term "magnetic field strength" is equivalent to the magnitude of the magnetic field vector, i.e. (in Cartesian coordinates)

$$H = (H_x^2 + H_y^2 + H_z^2)^{1/2}$$

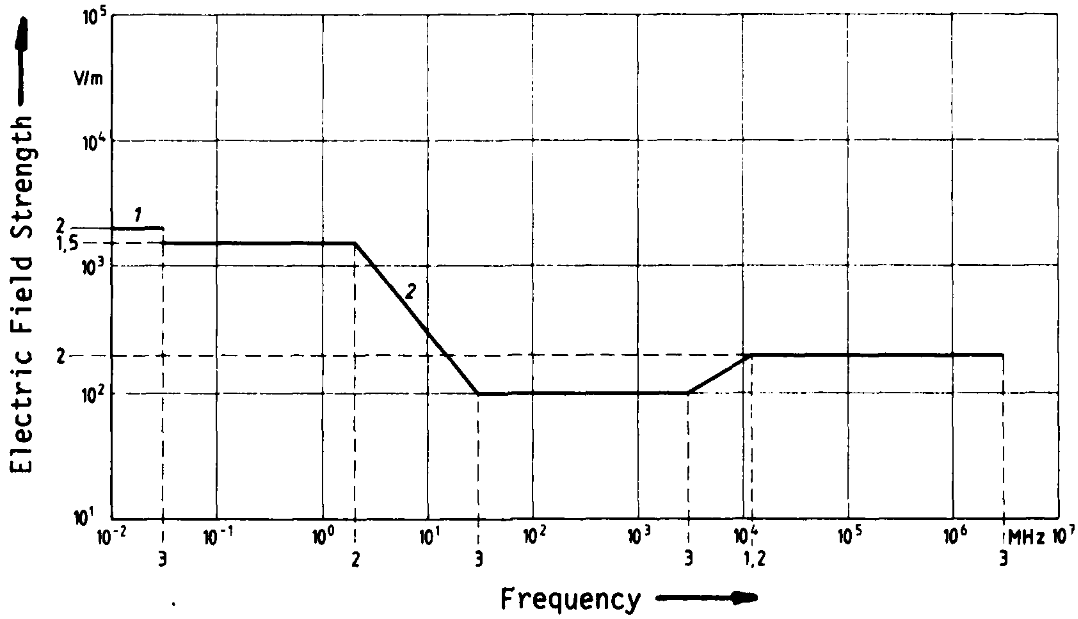

Fig. 1. Boundary value of the electric field strength

1. Maximum permissible peak value of the electric field strength in the frequency range 10 kHz $\leq f < 30$ kHz.
   1500 V/m is permissible as the maximum effective value for sinusoidal waveforms.

2. Maximum permissible effective value of the electric field strength in the frequency range 30 kHz$\leq f<$ 3000 GHz during exposure to the electromagnetic field $\geq$ 6 min.

Author's comment:
Referring to DIN 56 848 Part 1/VDE 0848 Part 1 throughout this VDE-rule (Part 2) the term "electric field strength" is equivalent to the magnitude of the electric field vector, i.e. (in Cartesian coordinates)

$$E = (E_x^2 + E_y^2 + E_z^2)^{1/2}$$

Larger limit values of the field intensities and power densities are permissible during exposure to the electromagnetic field < 6 min. Utilizing time average they are calculated for every 6-min interval as follows:

$$\sum_{i=1}^{n} E_i^2 \cdot t_i \leq 2{,}4 \cdot 10^5 \ (V/m)^2 \ min$$

$$\sum_{i=1}^{n} H_i^2 \cdot t_i \leq 1{,}5 \ (A/m)^2 \ min$$

$$\sum_{i=1}^{n} S_i \cdot t_i \leq 600 \ (W/m^2) \ min$$

n	Number of exposures within a 6-min interval
E_i, H_i	Effective value of the field strength during the i-th exposure (in V/m, A/m respectively)
S_i	Average value of the power density during the i-th exposure (in W/m^2)
t_i	Duration of the i-th exposure (in min)

3.2 LIMIT VALUE FOR THE INDIRECT HAZARD TO PERSONS FROM ELECTROMAGNETIC FIELDS

Contact voltage referring to DIN 57 866/VDE 0866/12.78. According to that, contact voltages of up to 72 V are considered harmless.

4. PREVENTIVE MEASURES AGAINST EXCEEDING THE LIMIT VALUES

For indoctrinated personnel the authorized areas must be clearly marked where the limit values will be exceeded. For other persons the areas where the limit values are exceeded must be put off limits and marked as hazardous.

Technical preventive measures are, e.g.
- Turning off the source of radiation
- Reducing output power of the radiation source
- Screening

Effectiveness of the implemented protective measures must be tested.

Effective value of the magnetic field strength $H = 0.25\sqrt{\frac{f}{3000}}$ A/m

or average value of the power density $S = 25 \cdot \frac{f}{3000}$ W/m^2

f Frequency in MHz

Larger limit values of the field intensities and power densities are permissible during exposure to the electromagnetic field < 6 min. Utilizing time average they are calculated for every 6-min interval as follows:

$$\sum_{i=1}^{n} E_i^2 \cdot t_i \leq 20 \cdot f \ (V/m)^2 \ \text{min}$$

$$\sum_{i=1}^{n} H_i^2 \cdot t_i \leq 1{,}25 \cdot 10^{-4} \cdot f \ (A/m)^2 \ \text{min}$$

$$\sum_{i=1}^{n} S_i \cdot t_i \leq 0.05 \cdot f \ (W/m^2) \ \text{min}$$

n	Number of exposures within a 6-min interval
E_i, H_i	Effective value of the field strengths during the i-th exposure (in V/m, A/m respectively)
S_i	Average value of the power density during the i-th exposure (in W/m^2)
t_i	Duration of the i-th exposure (in min)
f	Frequency in MHz

3.1.6 FREQUENCY RANGE 12 GHz ≤ f < 3000 GHz

The following limit values apply during exposure to the electromagnetic field ≥ 6 min:

Effective value of the electric field strength	200 V/m
Effective value of the magnetic field strength	0.5 A/m
or average value of the power density	100 W/m^2

3.1.4 FREQUENCY RANGE 30 MHz $\leq f < 3$ GHz

The following limit values apply during exposure to the electromagnetic field ≥ 6 min:

Effective value of the electric field strength	100 V/m
Effective value of the magnetic field strength	0.25 A/m
or average value of the power density	25 W/m^2

Larger limit values of the field intensities and power densities are permissible during exposure to the electromagnetic field < 6 min. Utilizing time average they are calculated for every 6-min interval as follows:

$$\sum_{i=1}^{n} E_i^2 \bullet t_i \leq 6 \bullet 10^4 \ (V/m)^2 \text{ min}$$

$$\sum_{i=1}^{n} H_i^2 \bullet t_i \leq 0{,}375 \ (A/m)^2 \text{ min}$$

$$\sum_{i=1}^{n} S_i^2 \bullet t_i \leq 150 \ (W/m)^2 \text{ min}$$

n	Number of exposures within a 6-min interval
E_i, H_i	Effective value of the field strengths during the i-th exposure (in V/m, A/m respectively)
S_i	Average value of the power density during the i-th exposure (in W/m^2)
t_i	Duration of the i-th exposure (in min)

3.1.5 FREQUENCY RANGE 3 GHz $\leq f < 12$ GHz

The following limit values apply during exposure to the electromagnetic field ≥ 6 min:

Effective value of the electric field strength $\quad E = 100\sqrt{\frac{f}{3000}}$ V/m

n	Number of exposures within a 6-min interval
E_i, H_i	Effective value of field strengths during the i-th exposure (in V/m, A/M respectively)
t_i	Duration of the i-th exposure (in min)
f	Frequency in MHz

3.1.3 FREQUENCY RANGE 2 MHz $\leq f <$ 30 MHz

The following limit values apply during exposure to the electromagnetic field $\geqq$ 6 min:

Effective value of the electric field strength $\frac{3000}{f}$ V/m

Effective value of the magnetic field strength $\frac{7,5}{f}$ A/m

f Frequency in MHz

Larger field strength limit values are permissible during exposure to the electromagnetic field < 6 min. Utilizing time average they are calculated for every 6-min interval as follows:

$$\sum_{i=1}^{n} E_i^2 \cdot t_i \leq \frac{5,4 \cdot 10^7}{f^2} \, (V/m)^2 \text{ min}$$

$$\sum_{i=1}^{n} H_i^2 \cdot t_i \leq \frac{337,5}{f^2} \, (A/m)^2 \text{ min}$$

n	Number of exposures within a 6-min interval
E_i, H_i	Effective value of field strengths during the i-th exposure (in V/m, A/m respectively)
t_i	Duration of the i-th exposure (in min)
f	Frequency in MHz

VDE 0848 Part 1 in order to determine the peak, effective, and average values.

Note: Hazard limit values for persons wearing artificial devices for bodily functions and having replacements for organs/limbs are being prepared.

3.1 LIMIT VALUES FOR DIRECT HAZARDS TO PERSONS FROM ELECTROMAGNETIC FIELDS

Refer to figures 1 to 3

3.1.1 FREQUENCY RANGE 10 kHz $\leq f <$ 30 kHz

Peak value of the electric field strength	2000 V/m
Effective value of the temporal sinusoidal waveform	1500 V/m
Peak value of the magnetic field strength	500 A/m
Effective value of the temporal sinusoidal waveform	350 A/m

For maximum exposure time of 5 minutes per hour, for arms and legs permissible peak value of the magnetic field strength is 5 kA/m

Note: In this frequency range peak values are the determining factors for the human hazard; the effective value figures have been rounded up.

3.1.2 FREQUENCY RANGE 30 kHz $\leq f <$ 2 MHz

The following limit values apply during exposure to the electromagnetic field $\geq$ 6 min:

Effective value of the electric field strength	1500 V/m
Effective value of the magnetic field strength	$\frac{7,5}{f}$ A/m

Larger field strength limit values are permissible during exposure to the electromagnetic field < 6 min. Utilizing time average they are calculated for every 6-min interval as follows:

$$\sum_{i=1}^{n} E_i^2 \cdot t_i \leq 1,35 \cdot 10^7 \ (\mathrm{V/m})^2 \ \mathrm{min}$$

$$\sum_{i=1}^{n} H_i^2 \cdot t_i \leq \frac{337,5}{f^2} \ (\mathrm{A/m})^2 \ \mathrm{min}$$

1. APPLICATION RANGE

This standard, characterised as a VDE-Rule, applies to protection of persons from hazards of electromagnetic fields of frequencies in the range 10 kHz to 3000 GHz. It is valid for protection of persons against direct and indirect hazards of electromagnetic fields.

It is not valid for intentional medical application of electromagnetic fields.

2. TERMS

2.1 GENERAL TERMS

Refer to DIN 57 848 Part 1/VDE 0848 Part 1

2.2 HAZARDS TO PERSONS FROM ELECTROMAGNETIC FIELDS

Effect of electromagnetic fields which can lead to bodily harm

2.2.1 DIRECT HAZARDS TO PERSONS FROM ELECTROMAGNETIC FIELDS

Hazards to persons from direct effects of electromagnetic fields

2.2.2 INDIRECT HAZARDS TO PERSONS FROM ELECTROMAGNETIC FIELDS

Hazards from touching objects (receiving structures) capable of conducting electric energy and in which voltage is produced by electromagnetic fields

2.3 LIMIT VALUE

Largest or smallest value of a given quantity within a given regulation.

Note: Hazards to persons can exist in exceeding the limit values stated as the highest permissible values.

3. LIMIT VALUES

The given limit values are valid for modulated and non-modulated electromagnetic fields. According to the state-of-the-art no hazards should be expected if these limit values are observed. Refer to DIN 57 848 Part 1/

APPENDIX to "RADIOFREQUENCY RADIATION SAFETY GUIDELINES IN THE FEDERAL REPUBLIC OF GERMANY" (Klaus W. Hofmann)

VDE 0848 Part 2	HAZARDS FROM ELECTROMAGNETIC FIELDS Protection of Persons in the Frequency Range from 10 kHz to 3000 GHz (VDE-RULE)	DIN 57 848 Part 2

This VDE-Rule is valid on 1 July 1984

Approved by the Directorate of the Union of German Electrotechnicians (VDE), a registered union, and announced in the Electrotechnical Journal

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1. In the frequency range below 30 kHz, theoretical considerations are based on the current-density concept (see contribution by J. Bernhardt, "Evaluation of Human Exposure to Low Frequency Fields," in this volume.

   In this frequency range a biological effect results from interaction of external fields with excitable nerve and muscle cells. Criterion for the stimulation of the cells will then be the electric field strength as induced inside the biological body, which is combined with the current density by the tissue's material properties. Threshold values for the stimulation of these cells are known from experimental and theoretical studies. Provided with an appropriate safety factor, exposure limits have been derived from these considerations. In Figures 1 and 2 of the standard, therefore, values permitted are expressed in terms of the electric and magnetic field strength respectively.

2. Above 30 kHz, especially for F > 2 MHz, the concept of absorbed energy serves as basis for setting exposure limits. This concept is based on methods of dosimetry, i.e., measurement and calculation of the internal RF-field in an irradiated body, where the results are expressed in terms of the specific absorption rate (SAR) in watts/kilogram. This concept is well described in the preceding paper of Prof. Carl H. Durney ("Physical Interactions of Radiofrequency Radiation Fields and Biological Systems"). In his contribution "Radiofrequency Radiation Standards" in this volume, John C. Mitchell gives an overview about the development of several RFR standards, which mainly use SAR as a common denominator for biological effects. Most of them accept the average whole-body absorption to 0.4 W/kg as a limit. It should, therefore, be noted that the West German standard takes a value of 1 W/kg as a basis. This may explain some differences between this standard and the ANSI standard, which are both derived from the same concept. Figure 3 of the standard is given in terms of average power density as a function of frequency beginning at f = 30 MHz.

In the interim range between 30 kHz and 2 MHz, limits are established so that they do not exceed values given by application of either only the thermal concept or the concept of nerve stimulation.

Concluding this introduction to the new German standard, the text of DIN 57848 Part 2/VDE 0848 Part 2 is added as an appendix.[5] In this text, particular attention should be directed to paragraph 1, "Application Range," where no difference is made between occupational workers and the general public.

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[5]The very kind assistance of the U.S. Air Force School of Aerospace Medicine, San Antonio, Texas, for getting it translated is gratefully appreciated.

Part 3 is still under discussion. There exists only a first draft of August 1983. It includes guidelines for the protection against explosive gas-air mixtures, ignitable by sparks at spacings between receiving parts; for instance, metallic constructions at service stations, refineries, etc.

Part 4 of DIN 57848 deals with electroexplosive devices (unintended ignition from RF fields) and is still under consideration.

These four parts are to be seen as a whole because they cover both kinds of biological effects of radiofrequency radiation, direct and indirect effects.

Historically, work on this standard started in 1975, when Committee 764 of German Electrotechnical Commission established a working group to collect information and experience in the field of RFR standards. Progress was made in 1977 when this working group got knowledge of NATO-STANAG 2345, as developed by the recent Research Study Group 1 of NATO Panel VIII. Based on this information and studies of current literature, a first draft of a German standard with frequency-dependent exposure-limiting values was published in 1978. This paper was selected to replace a guide with the very early 10-mW/cm^2 standard, edited by DGON[3] in 1962. Public discussion began; the working group had to wait for objections from the public, had to review these contributions, had to take them into consideration, and had to compare the results of succeeding work once more with new findings published in the literature. After several drafts, the present standard (here part 2 of DIN 57848) was brought into practice this year.

As already mentioned, this short paper is not intended to explain fundamental theory that led to these safety rules, especially since there exists a more comprehensive report[4] of the Institute of Radiological Health of the Federal Health Office. But the following brief summary shall point out on which concepts the standard is based.

Considering farfield and nearfield conditions, exposure to electromagnetic fields can be quantified by measuring power density--electric and magnetic field strengths. Discussing whether these measured (or calculated) quantities are dangerous to exposed biological systems or not, current literature and experience show that threshold values can be defined which mark a borderline between "safe" and "hazardous" levels of radiofrequency field quantities.

In setting these frequency-dependent limits, two basic concepts have been applied:

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[3]DGON = Deutsche Gesellschaft fuer Ortung und Navigation (German Association for Radar and Navigation).

[4]J. H. Bernhardt, M. Dahme, F. K. Rothe: "Gefährdung von Personen durch elektromagnetische Felder." Report No. 2/1982 of the Institute of Radiological Health (Institut fur Strahlenhygienen des Bundesgesundheitsamtes).

TABLE 2. CONVERSION OF POWER DENSITY TO ELECTRIC FIELD STRENGTH AND SQUARED ELECTRIC FIELD STRENGTH*

Power Density (mW/cm^2)	Equivalent Electric Field Strength, E, or Squared Field Strength, E^2 (round numbers)	
	E (V/m)	E^2 (V^2/m^2)
1	60	4 000
2	90	8 000
5	140	20 000
10	200	40 000
25	300	90 000
33	350	120 000
66	500	250 000
165	800	600 000

*Data taken from Fig. 3-2 of [2]

(3) Two exclusions to the PELs are permitted. These are (from paras 4.2(1) and (2) of [4]):

(a) At frequencies between 300 kHz and 100 GHz, the PELs may be exceeded if the exposure conditions can be shown by laboratory procedures to produce specific absorption rates (SARs) below 0.4 W/kg as averaged over the whole body, and spatial peak SAR values below 8 W/kg as averaged over any one gram of tissue.

(b) At frequencies between 300 kHz and 1 GHz, the PELs may be exceeded if the radiofrequency input power of the radiating device is seven watts or less.

INITIAL SAFETY ASSESSMENTS

AN/PRC-77 VHF Transceiver

The AN/PRC-77 is an FM transceiver operating from 30 to 76 MHz. It is considered safe because it radiates no more than four watts of RF power, which is less than the seven watts permitted in para 3(b) above.

AN/PRC-515 HF Transceiver

This set transmits AM radiation (CW or SSB) in the HF band (2-30 MHz). Since it radiates 20 to 30 watts in the high-power mode, it is not excluded from the exposure standard based on the amount of radiated power (para 3(b), Introduction).

The exposure fields for the AN/PRC-515 used with the eight-foot whip antenna were measured by QETE. High electric-field exposures were found [5]. For the case of the radio set worn on the operator's back, the measured fields at the back of the operator's head were found to exceed the exposure limits. This is illustrated in Table 3, where four of the measurements were made by QETE [5] and the other two measurements (at 4 and 8 MHz) were done by a DND contractor in a subsequent study [6].

TABLE 3. COMPARISON OF MEASURED AND PERMITTED ELECTRIC EXPOSURE FIELDS FOR THE AN/PRC-515 MANPACK TRANSMITTER

Frequency (MHz)	Squared Electric Field (1000 V^2/m^2) Permitted Exposure 6 min	Squared Electric Field (1000 V^2/m^2) Permitted Exposure 1 min	Squared Electric Field (1000 V^2/m^2) Measured Exposure*
2	250	600	560**
4	40	90	(780)***
8	40	90	(330)
12	8	20	270
20	8	20	90
30	8	20	15

* Measured 20 cm from the 8' whip antenna, at the back of the operator's head. Transmitter used in the high-power (20-30 W) CW mode.

** Data taken from Table 2 of ref. 5.

*** Data in brackets taken from pp. 80 and 81 of ref. 6 (scaled up from low power to high power).

It is obvious from the data in the table that even the one-minute exposure limits are often exceeded.

At this point, the only remaining options are to restrict the use of the AN/PRC-515 for high-power transmissions or to study the safety of the set by the techniques outlined in para 3(a). The latter approach was taken --the specific absorption rates in models of the human body were determined

by laboratory procedures and the results compared to the SAR limits given in para 3(a) of the introduction of this report.

SPECIFIC-ABSORPTION-RATE STUDIES

General

Dr. S.S. Stuchly, of the University of Ottawa, was contracted by DREO to determine the SAR distribution in models of man exposed to the radiation fields of the AN/PRC-515. His group constructed two models of the human body and filled them with gel materials representing the average dielectric properties of the human body. To test the realism of one of the models, DREO measured its whole-body absorption rate inside a very large exposure facility used for measuring human whole-body RF absorption rates [7]. The model was found to absorb at a rate that is 50 percent greater than the rate measured for the average human subject [8]. Thus we will assume that the model also absorbs 50 percent more than a man would when exposed to the near-field radiation from a manpack source.

The effect of a helmet on the SAR in the head could not be tested because there was no way to realistically fit a helmet around the head of the models.

The effect of a rifle carried on a man's shoulder was simulated, and the metal barrel was shown to cause negligible changes in the pattern of RF absorption in the body.

Peak SAR

Both the exposure-field patterns and the SAR distribution were found to be quite uniform. Thus, no hot spots with a peak SAR > 8 W/kg were found.

Whole-Body Average SAR

For continuous operation at low power at all frequencies (2 - 30 MHz), the whole-body average SAR did not exceed the limit of 0.4 W/kg. For continuous operation at high power, the same result was obtained at frequencies from 4 to 30 MHz.

On the other hand, for continuous high-power operation at 2 MHz, the whole-body average SAR values, summarized in Table 4, were found to exceed the limit of 0.4 W/kg.

TABLE 4. WHOLE-BODY AVERAGE SAR FOR HIGH-POWER OPERATION OF THE AN/PRC-515 AT 2 MHz

Transmitter On	Human Model*	SAR (W/kg)	
		Continuous Operation	Duty Cycle OF 1/6
Shoulders	simple	1.5 - 2.3	0.25 - 0.38
	better	0.4 - 1.1	0.07 - 0.18
Ground	simple	0.3 - 0.6	0.05 - 0.10
	better	0.7	0.12

*The better model has a more realistic shape and uses two different dielectric materials for the brain and the body.

The SAR limit of 0.4 W/kg is intended to be averaged over any six-minute period, thus it is necessary to correct for the transmitter duty cycle. The standard operating procedure for the AN/PRC-515 limits transmissions to 30-second duration. The design duty cycle (transmission time/receive time) is 1/9. Under adverse operating conditions the worst-case duty cycle may be taken to be 1/6. Therefore, any given set is unlikely to transmit more than one minute out of every six-minute period.

The continuous-exposure SAR data of Table 4 have been corrected, in the last column, to take into account this worst-case duty cycle. The highest SAR values are reduced to 0.38 W/kg for the set used on the shoulders and to 0.12 W/kg for the set used on the ground. It should also be noted that these figures are likely high by about 50 percent, due to the inexactness of the model as explained earlier.

SAFETY CONCLUSIONS

From the SAR results, it is concluded that there is no radiofrequency radiation hazard for the AN/PRC-515 under any practical operating condition. The other warnings issued with the set should still be observed, of course. These include the danger of RF burns from touching the antenna, especially at the lower frequencies, and the possibility of electrocution should the whip antenna touch bare overhead power lines.

The AN/PRC-77 is also considered safe because it radiates only four watts of RF power. This conclusion is supported by the contractor's estimate that the SAR in a body exposed to a radiating AN/PRC-77 is only a few milliwatts/kilogram.

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3. Safety Code 6 - Recommended Safety Procedures for the Installation and Use of Radiofrequency and Microwave Devices in the Frequency Range 10 MHz - 300 GHz, Publication 79-EHD-30, Health and Welfare Canada, 1979.

4. American National Standard - Safety Levels with Respect to Human Exposure to Radiofrequency Electromagnetic Fields (300 kHz - 100 GHz), ANSI standard C95.1 - 1982.

5. Non-Ionizing Radiation Levels Near Manpack Sets AN/PRC-77 and AN/PRC-515, 26 Jun 80, QETE project A02307.

6. G. Hartsgrove and S.S. Stuchly, Final Report - Radiofrequency Absorption Studies for Two Portable Radiocommunications Sets, The University of Ottawa, Department of Electrical Engineering, June 1983.

7. D.A. Hill, "Human Whole-Body Radiofrequency Absorption Studies Using a TEM-Cell Exposure System", IEEE Trans. Microwave Theory Tech., Vol. 30, pp. 1847-1854, 1982.

8. D.A. Hill, "The Effect of Frequency and Grounding on Whole-Body Absorption of Humans in E-Polarized Radiofrequency Fields", Bioelectromagnetics, Vol. 5, pp. 131-146, 1984.

III. PANEL DISCUSSIONS

ON THE PREDICTION OF HUMAN RESPONSES TO RFR

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Since it is considered to be morally indefensible to deliberately expose human beings to controlled RF fields for the assessment of biological consequences, it is necessary to use other means to predict potential consequences. Data derived from animal experiments have been useful in the past and will continue to be an important predictive source. For example, a major consideration in the formulation of the current ANSI Standard was the phenomenon of "work stoppage" (e.g., de Lorge, 1983). Ongoing, food-motivated operant behavior is reliably disrupted by RF exposure at an SAR (~4 W/kg) that elevates the internal body temperature of the behaving animal by about 1 °C. Since work stoppage has been demonstrated in several animal species, it appears to have good predictive value for the human condition.

Not so successful was a recent attempt by Gordon (1982) to extrapolate data derived from the laboratory mouse to man on the basis of differences in body mass. Gordon's experiment, summarized elsewhere in this volume (Adair, p. 50), determined a "threshold" of 29 W/kg for the initiation of evaporative heat loss (EHL) in mice exposed to 2.45-GHz microwaves at an ambient temperature (T_a) of 20 °C. He then constructed a plot of SAR <u>vs</u> body mass (Figure 5 in Gordon, 1982) that displayed this "threshold" together with "thresholds" for initiation of other responses (thermoregulatory and nonthermoregulatory, physiological and behavioral) of mice, rats, rabbits, squirrel monkeys, and simulated men (Spiegel et al., 1980). These species had been exposed to diverse microwave fields in T_a that ranged from 20 to 35 °C. The function calculated from these data was alleged to predict that EHL (sweating) would be initiated in a 70-kg human exposed in a 20 °C environment to RFR at an SAR of approximately 0.25 W/kg. In a follow-up report (Gordon, 1983), additional data gleaned from the literature were presented in a set of functions which, when extrapolated, predicted a 5-fold range of SARs (0.06 to 0.30 W/kg) to initiate different thermoregulatory responses in a 70-kg human. Recent unpublished data from several laboratories not only indicate a very low correlation between SAR and body mass but sometimes a reversed functional relationship, i.e., that SAR may <u>increase</u> with mass when the relevant variables are properly controlled.

This unsuccessful attempt to extrapolate animal data to the human condition ignored the dependence of thermoregulatory processes on the prevailing T_a and the unique thermophysiological profiles of individual species (Adair et al., 1983; 1984). This approach also assigned paramount importance to possible differences between RFR and conventional forms of heat stress such as exercise or elevated T_a. It now appears highly unlikely that any SAR-<u>vs</u>-body mass function can be given so much precision that extrapolation over several orders of magnitude will become the method of choice for predicting human thermoregulatory responses to RFR. The use of sophisticated simulation models of the human thermoregulatory system (e.g., Stolwijk and Hardy, 1977) coupled to a block model of RFR-energy deposition (e.g., Gandhi, 1982), together with the assumption that RFR is equivalent to other forms of thermal energy, would seem a far more precise alternative.

Controlled RFR exposure of human volunteers must ultimately be conducted to validate specific predictions of human physiological responses and psychological reactions. Buffler and Lentz (1984) have recently confirmed the technical feasibility of Pound's (1980) proposal to provide RF comfort heating of humans in otherwise cold interior spaces. They determined the threshold of just-perceptible warming to be 25 mW/cm^2 when the whole body was exposed to

2.45- or 10-GHz microwaves within a room-sized metal cavity. This value is the same as that reported in classical psychophysical studies (Hendler and Hardy, 1960; Eijkman and Vendrik, 1961; Hendler, Hardy, and Murgatroyd, 1963) and more recently by Justesen et al. (1983). Although their observations were preliminary, Buffler and Lentz could detect no deleterious physiological or psychological sequelae to these controlled RF exposures.

Certain physiological thermoregulatory responses were monitored during exposures of myself to 2.45-GHz CW microwaves at two power densities, 13 and 52 mW/cm^2. The former deposited energy at a rate that had been predicted by Spiegel et al. (1980) to initiate a thermoregulatory response, and the latter was judged to be the equivalent of 1 MET (1 times the resting metabolic rate). The bikini-clad, seated subject was equilibrated to a T_a of 25 °C and then irradiated dorsally for 35 (13 mW/cm^2) or 50 (52 mW/cm^2) minutes while measures of rectal temperature (T_{re}), chest and back skin temperatures (T_{ch} and T_{bk}), and sweating rate from the chest were recorded continuously.

At the lower intensity, a vague sensation of warmth was detected as T_{bk} rose slightly, but no change occurred in T_{re} or T_{ch} and sweating was not initiated despite Spiegel et al.'s prediction and that of Gordon's (1982) SAR vs body mass function. The sensation derived from the higher intensity could best be described as a delightful glow, akin to strong solar irradiation on a cool day at the beach. Although T_{re} rose about 0.8 °C during the 50-min exposure (attributable primarily to a 6.5 °C rise in T_a rather than to the imposed irradiation), more than 20 minutes elapsed before chest sweating was initiated; the sweating response prevented further increases in skin and body temperatures. Further experimentation of this type will be invaluable to the evaluation of predictions based on animal data or simulation models and must ultimately be applied to the formulation of acceptable standards for RF exposure of human populations.

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SOME RECENT REPORTS OF LOW-LEVEL RFR EFFECTS

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A criticism that has been repeatedly made of most, if not all, of the present electromagnetic exposure safety standards is that the reported biological effects of low-level electromagnetic irradiation have not been adequately considered in the setting of these standards. A significant number of low-level effects have been published, especially recently. At some point in the setting of safety standards, those who are formulating the standards must come to grips with the problem of how to evaluate the reported low-level effects and how to determine their relevance to safety standards. The purpose of these remarks is to cite five recent papers as examples of recently reported low-level effects and to make some comments about them. Only a few of the results contained in the papers will be mentioned.

1. J. Delgado, J. Leal, J. Monteagudo, and M. Gracia, "Embryological changes induced by weak, extremely low frequency electromagnetic fields," Journal of Anatomy 134: 533-551 (1982). The authors exposed fertilized chicken eggs to pulsed magnetic fields with 0.5-ms pulse width and frequencies of 10, 100, and 1,000 Hz, and intensities in the micro tesla range. At 1.2 micro tesla and 100 Hz, for example, they found strong inhibitory effects on embryogenesis in the chicken eggs. Replication of these effects at two different laboratories in the United States failed. Similar effects were observed in Sweden.

2. A. H. Jafary-Asl, S. N. Solanki, E. Aarholt, and C. W. Smith, "Dielectric measurements on live biological materials under magnetic resonance conditions," Journal of Biological Physics 11: 15-22 (1983). In the dielectrophoretic yield in live yeast cells an anomaly was found at frequencies corresponding to the nuclear magnetic resonance frequency of protons. The anomaly was not seen in dead yeast cells. The authors also found that the presence of a dc magnetic field affected the real and imaginary parts of the dielectric constant of live, but not dead, yeast cells. They also found magnetic resonance effects on growth of yeast cells and on a lysozyme reaction. The exposure levels were typically in the range of micro tesla. Researchers working in NMR (nuclear magnetic resonance) generally seem to agree that the reported effects are not likely to be NMR effects because the energy of a proton in the low values of dc magnetic field used in the experiments is eight or nine orders of magnitude below kT.

3. Blackman, Benane, Rabinowitz, House, "The influence of the earth's magnetic field in the radiation-induced efflux of calcium ions from brain tissue in vitro," submitted for publication (1984). The authors have found in this and previous work that exposure to magnetic fields at 15, 45, 75, and 105 Hz at levels in the micro tesla range cause changes in calcium efflux to occur at certain levels of intensity. Most recently they found that the frequencies at which changes in calcium efflux occur are directly related to the dc magnetic field that is present.

4. A. R. Liboff, T. Williams, Jr., D. M. Strong, R. Wistar, Jr., "Time-varying magnetic fields: effect on DNA synthesis," Science 223: 818-820 (1984). In human fibroblasts the authors found that sinusoidal magnetic fields at frequencies from 15 Hz to 4 kHz and at intensities from 2.3 to 560 micro tesla caused enhanced DNA synthesis. They also showed that the enhancement appeared to be independent of dB/dt, indicating that the effect is probably not related to induced eddy currents.

5. F. Keilmann, "Triplet-selective chemistry: a possible cause of biological microwave sensitivity," submitted to IEEE Transactions on Microwave Theory and Techniques (1984). In previous work the author and his colleagues showed that microwave irradiation at intensities less than 10 mW/cm^2 and at frequencies near 42 GHz causes a nonthermal, narrow-band (8MHz) effect on the growth of yeast cells. In this paper the author proposes a model to explain these and possibly other biological effects. The model is based on thermal nonequilibrium of triplet states.

Some comments about this group of papers:

1. Many questions are being asked about most or all of these papers.

2. Many of these results are quite unexpected.

3. Many of these results have not been replicated.

4. Many of the results must be considered to be preliminary until better understood.

These conjectures could be made about this group of papers:

1. These results may be related to a common magnetic-field effect.

2. The ambient dc magnetic field may be an important parameter in electromagnetic biological effects.

3. If real, some of these effects may lead to better understanding of the underlying basic mechanisms of interaction of electromagnetic fields and biological systems.

At which point in time effects like these should be considered in setting safety standards is an important question for this group to consider.

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